

THE EXTENSIBILITY OF THE

ARTERIES IN MAN

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# C O N T E N T S

— o O o —

|                                      | Page |
|--------------------------------------|------|
| PREFACE . . . . .                    | vii  |
| SECTION I.                           |      |
| INTRODUCTION:                        |      |
| Historical survey .. . . .           | 2    |
| Present investigation .. . . .       | 18   |
| SECTION II.                          |      |
| METHOD:                              |      |
| The principle and its application .. | 22   |
| Instruments . . . . .                | 25   |
| Method of taking records . . . . .   | 40   |
| SECTION III.                         |      |
| EXPERIMENTAL RESULTS:                |      |
| The evolution of the technique ...   | 72   |
| Pulse wave velocity in the arm ...   | 81   |
| Pulse wave velocity in the leg ...   | 120  |

## SECTION IV.

## HISTOLOGICAL INVESTIGATION:

|              |        |     |
|--------------|--------|-----|
| Introduction | ... .. | 124 |
| Conclusions  | ... .. | 130 |

## SECTION V.

## DISCUSSION:

|                                   |        |     |
|-----------------------------------|--------|-----|
| The pulse wave                    | ... .. | 134 |
| The function of the arteries      | ... .. | 137 |
| The extensibility of the arteries | ... .. | 141 |
| Clinical application              | ... .. | 156 |
| Summary and conclusions           | .. ..  | 160 |
| BIBLIOGRAPHY                      | ... .. | 168 |

---

# LIST OF ILLUSTRATIONS

— oOo —

| No. |  | Page |
|-----|--|------|
| 1   | Simple wiring diagram .. .. .                | 23   |
| 2   | Hot-wire container .. .. .                   | 29   |
| 3   | Receiver for carotid artery .. .. .          | 35   |
| 4   | Receiver for radial pulse .. .. .            | 35   |
| 5   | Arrangement for records from brachial artery | 36   |
| 6   | Receiver for brachial artery .. .. .         | 36   |
| 7   | Receiver for femoral artery .. .. .          | 37   |
| 8   | Receiver for popliteal and dorsalis pedis .. | 37   |
| 9   | General arrangement for respiratory records  | 38   |
| 10  | General arrangement of room .. .. .          | 41   |
| 11  | Measurement points in the arm .. .. .        | 44   |
| 12  | Optical record of carotid artery .. .. .     | 50   |
| 13  | Hot-wire record of carotid artery .. .. .    | 50   |
| 14  | Distortion of simultaneous records .. .. .   | 52   |
| 15  | Receiver for simultaneous records .. .. .    | 54   |
| 16  | Simultaneous optical and hot-wire record ..  | 55   |
| 17  | Hot-wire record from brachial artery .. ..   | 57   |
| 18  | Hot-wire record from radial artery .. .. .   | 57   |
| 19  | Hot-wire record from whole arm .. .. .       | 57   |



| No. |   | Page |
|-----|---|------|
| 20  | Hot-wire record from brachial artery .. ..    | 58   |
| 21  | Hot-wire record from radial artery .. ..      | 58   |
| 22  | Hot-wire record from whole arm .. ..          | 58   |
| 23  | Brachial record with respiratory tracing ..   | 59   |
| 24  | Radial record with respiratory tracing .. ..  | 59   |
| 25  | Whole arm with respiratory tracing .. ..      | 59   |
| 26  | Hot-wire record from femoral artery .. ..     | 60   |
| 27  | Hot-wire record from anterior tibial artery . | 60   |
| 28  | Hot-wire record from whole leg .. ..          | 60   |
| 29  | Record using three strings simultaneously ..  | 61   |
| 30  | Three string record with respiratory tracing  | 61   |
| 31  | Measurement point in hot-wire records .. ..   | 63   |
| 32  | Arrangement for respiratory & B.P. records .. | 87   |
| 33  | Respiratory variation in blood-pressure .. .. | 88   |
| 34  | Respiratory variation in blood-pressure .. .. | 89   |
| 35  | Effect of respiration on pulse-wave velocity  | 92   |
| 36  | Age & pulse-wave velocity in brachial .. ..   | 102  |
| 37  | Age & pulse-wave velocity in radial .. ..     | 104  |
| 38  | Age & pulse-wave velocity in whole arm .. ..  | 106  |
| 39  | Age & pulse-wave velocity from averages .. .. | 109  |
| 40  | Extensibility of arteries at different ages   | 113  |
| 41  | Effect of change of posture of arm .. ..      | 118  |
| 42  | Effect of change of posture of arm .. ..      | 119  |

# LIST OF TABLES

— ooo —

| No. |  | Page |
|-----|--|------|
| 1   | Effect of pressure in receiver at elbow ..   | 75   |
| 2   | Protocol of experiment to test accuracy ..   | 77   |
| 3   | Summary of experiments in upper limb .. ..   | 78   |
| 4   | Summary of experiments in lower limb .. ..   | 79   |
| 5   | Respiratory variation in pulse-wave velocity | 91   |
| 6   | Pulse-wave velocity in group aged 20 years.  | 94   |
| 7   | Pulse-wave velocity, subjects 5-15 years..   | 97   |
| 8   | Pulse-wave velocity, subjects 15-25 years..  | 98   |
| 9   | Pulse-wave velocity, subjects 25-35 years..  | 99   |
| 10  | Pulse-wave velocity, subjects 35-45 years..  | 100  |
| 11  | Pulse-wave velocity, subjects 45-55 years..  | 100  |
| 12  | Pulse-wave velocity, subjects 55-65 years..  | 101  |
| 13  | Pulse-wave velocity, subjects 65-80 years..  | 101  |
| 14  | Summary of averages of tables 7-13 . . . .   | 108  |
| 15  | Mean extensibility in different age groups.. | 111  |
| 16  | Effect of change of posture of arm .. . . .  | 117  |
| 17  | Pulse-wave velocity in the lower limb .. ..  | 121  |

## THE EXTENSIBILITY OF THE ARTERIES IN MAN

The thesis consists of two volumes:-

VOLUME I is composed of five sections and at the beginning of each section a brief sketch is provided, showing the manner in which the subject matter of the section is arranged.

Section I is introductory and consists of a brief historical outline of the subject, with some remarks on the scope and aim of the present work.

Section II deals with the method.

Section III contains the experimental results with a foreword on the evolution of the technique.

Section IV contains the results of an investigation into the histological structure of the arteries.

Section V consists of a discussion on the results obtained, together with a summary and a list of references alphabetically arranged.

VOLUME II is comprised of a collection of photomicrographs of sections of human arteries which have been investigated histologically, together with notes on each slide.

I should like to take this opportunity of expressing my indebtedness to Professor B. A. McSwiney of Leeds University for the facilities which he has placed at my disposal. His unfailing interest and encouragement have been most stimulating, and his advice and criticism have proved invaluable to me in this research.

J. S. FULTON.

VOLUME ONE

— oOo —

SECTION

ONE

— oOo —

## I N T R O D U C T I O N

### HISTORICAL SURVEY:

Early references.

Pioneer work.

Improvements in technique.

### THE PRESENT INVESTIGATION:

Reason for investigation.

Scope of the work.

Source of material.

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The exact role of the arteries in the scheme of the circulation has long been a subject of dispute, resulting at times in violent controversy, and it is possible that, to the present day, the various factors involved even in the normal functioning of this system are not fully appreciated.

It is interesting to note that as early as 300 B.C. there was a conception in Greek medicine (Erasistratus) that the pulse in parts of the body near the heart appeared earlier than at the extremities.

Harvey published his masterly work on the circulation three hundred years ago, but two hundred years later, as evidenced by the writings of Kerr (73) and others, we find that his teachings were by no means universally accepted, and the medical world was actively engaged with the problem of the possible muscular structure of the arteries, their power of contraction and possible function in propelling the blood forward largely independent of the action of the heart.

Hunter (69) in 1824, writing on the subject of the muscularity of the arteries, states "that the heart is a most useful organ .... is undeniable - it is a useful reservoir for the blood vessels and, by its strength and excessive irritability, is admirably adapted for maintaining in the vessels a constant and equable supply of blood, as well as powerfully assisting the sanguinary movement."

Marshall Hall (55), as late as 1832, gives it as his opinion that "the arteries are indeed a second heart in elongated form" containing muscular tissue and capable of independent contraction.

Still more interesting is the paper published by Hawley (57) four years later, in which he ascribes to the blood an inherent vital self-motive power.

The other school of thought, however, was not without its supporters at this time, and as early as 1822 we find Beclard (7) in France expressing the view that the arteries are essentially elastic in structure.

McFadyen (93) in 1824 definitely asserts that "the arteries by their elastic property assist in



carrying forward the vivifying current."

Corrigan (25) also appears to have held this opinion when in 1832 he referred to the elasticity of the brachial arteries as a factor in the production of the typical pulse of Aortic Incompetence.

Flourens (44) about the same time investigated the subject of the "Motion and Beating of the Arteries." He described the pulsation of an artery as consisting of three primary actions - dilatation, displacement and elongation. A flexible watch spring ring was fitted closely round an artery. The ring was split at one point, and thus dilatation of the artery was indicated by separation of the cut ends of the ring. He showed that displacement of an artery occurred especially at flexures such as the Aortic Arch and in the vessels of the mesentery, and that with each impulse the vessel tended to straighten. Thirdly, he marked with colour a point on the exposed carotid, and, fixing a needle below it, observed the coloured portion alternately advance and retire. In summing up, he

states that "all the actions constituting the compound action of an artery may be accounted for by the impulse of the blood and the elasticity of the vessel. The beating or whole motion of an artery depends upon its elasticity."

Weber (118), however, in 1834, was probably the first to recognise the true nature of the pulse-wave and to measure its velocity. He used palpation of the pulse and took the time on an ordinary watch between the occurrence of the impulses in the External Maxillary and Dorsalis Pedis arteries. Considering the very great possibilities of error associated with this method, it is of interest to note that his estimation of the general rate of propagation of the pulse-wave as being 8-9 metres per second was remarkably accurate.

In 1860, Marey (88) in France introduced the sphygmograph, and this permitted the pulse-wave to be recorded graphically by means of a system of tambours and levers.

Buissons (21) in 1861 first applied graphic methods to the investigation of the velocity of the

pulse-wave, employing Marey's tambours as receivers, and conveying the impulse through tubes to other tambours, records being taken on smoked paper with a revolving drum.

Other observers followed up his investigations; Czermak (26) and Waller (117) used practically the same method, but Keyt (75) used water instead of air in his receivers and tubes.

Landois (78) impressed by the error due to friction when recording on smoked paper, and realizing the difficulty of determining in sphygmographic tracings the exact point of commencement of the pulse-wave for measurement purposes, devised an electro-magnetic method, in which the mercury contact-breaker was operated by the sphygmograph. By this procedure, however, it is impossible to eliminate error occasioned by an alteration in the form of the pulse-wave, and the method was discarded by later observers.

About this time, the investigation of the elastic properties of the blood vessels was approached from another angle. Braune (9) in 1874 investigated the elasticity of veins by

stretching the vessel longitudinally and obtained curves of extensibility which were at first proportional to the weights applied, but with increasing weights tended to become hyperbolic. Bardeleben (1) on the other hand, in experiments carried out in 1877, obtained parabolic curves.

Roy (106) in 1880 investigated the elasticity of the arteries in a similar manner. He obtained curves of extensibility by stretching portions of arterial wall both longitudinally and transversely. He showed that, unlike metallic substances, the organic material constituting the arterial wall did not behave in accordance with the law of Hooke, and that successively increasing weights produced a gradually diminishing effect with regard to the stretching of a portion of artery. He also pointed out that the extensibility curves obtained from longitudinal strips of artery differed from those obtained from corresponding transverse strips.

Roy also demonstrated graphically the relation between internal pressure and internal cubic capacity in portions of excised carotid artery,

showing that a rise in pressure caused an increase in the capacity of the artery. Furthermore, this observer showed that the most marked effect was produced with internal pressures corresponding to those normally prevailing during life in the vessel under consideration.

Roy described the phenomenon of "after action" in which an elastic structure continues to expand slowly in response to stretching, but his results are impaired in that he limited his observations to the effects of slow changes in pressure on the arterial wall, whereas during life the vessel wall is being continually subjected to rapid alterations in pressure.

Moens (91), about the same time, drew attention to the fact that the extensibility of the blood vessels was related to the pulse-wave velocity, and that these two factors were further related to the blood pressure. His treatment of the problem was very thorough, and he carried out investigations both on an artificial scheme and in the human subject. As a result of his investigations, Moens definitely related the elasticity of

an artery to the pulse-wave velocity, and, for the purpose of investigating the extensibility in arteries, suggested the following formula:

$$M = K \sqrt{g \frac{Ea}{\Delta d}}$$

Where M = Velocity of pulse-wave

K = A constant

g = Acceleration due to gravity

E = Coefficient of elasticity

a = Thickness of vessel wall

$\Delta$  = Density of the fluid

d = Diameter of vessel

This equation unfortunately contains several factors which could not be determined in the living subject, and it is therefore not possible to apply the formula in the clinical investigation of the state of the arterial wall.

The work of Roy and Moens was of considerable importance, as these observers were the first to make an accurate experimental study of the function of arterial extensibility. Their conclusions led the way not only to a better understanding of the problem, but opened out the experimental field.

Grunmach, (51) (52) (53), later showed that in the case of an artery, the effect of bore and thickness of wall is almost negligible, relative to that of the coefficient of elasticity. This observation practically brought the original formula of Moens to a state in which it could be applied in the investigation of the extensibility of the arteries during life. Grunmach, in his observations of the human being, largely adopted the original method of Buisson, using smoked paper on a revolving drum, but he employed an improved time-marking device.

Marey (89) in 1881, in a critical study of the pulse-wave and pulse-wave velocity, showed that the delay between the occurrence of the cardiac impulse and the arrival of the pulse-wave in different parts of the arterial system depended on the distance of the artery from the heart. Marey also evolved an artificial scheme whereby pressure, density and rate of flow could be varied.

Franck (45), Rivals (101) and others extended these observations and obtained records of the pulse-wave velocity from the apex beat to the



peripheral arteries, both in physiological and pathological conditions. In their results, however, these observers took no account of isometric ventricular contraction, which has been shown by Weitz (119) (120), Wiggers (121) (122) and others to vary considerably.

Optical methods were introduced by Franck (46) (47) in 1905, and this marked a further step in the progress of accuracy by largely eliminating the sources of error in the form of friction and inertia, associated with the methods of previous observers.

Ruschke (107) in 1912 applied photographic methods and recorded the movement of a light lever fixed to a tambour. The disadvantage of this method lay in the fact that the experiment had to be conducted in a dark room.

The advent of the paper camera and the falling plate device used in electrocardiography removed this difficulty, and subsequent observers have almost universally adopted this method of recording.



Lundsgaard and Beyerholm ( 85 ) recorded the movements of tambour levers by projecting the shadows of these levers on the face of the camera, but the results of their observations do not inspire confidence in the accuracy of the method.

In 1923, Bazett and Dreyer ( 5 ) used a similar method for the investigation of pulse-wave velocity in different arteries under normal and abnormal conditions. In their later experiments, however, these observers employed modified Frank's capsules, a beam of light being reflected on to the face of the camera from a small galvanometer mirror fixed on the edge of the rubber diaphragm of the capsule. The bulging of the diaphragm caused by the pulse wave resulted in a deflection of the image on the sensitive paper of the camera. Bazett and Dreyer attempted to relate their estimations of the pulse-wave velocity in the arm to results obtained by other observers on the excised carotid artery, but suggested, however, that the velocity of the pulse wave was higher in the peripheral arteries than in the large vessels.

While engaged in counter battery work in France in 1916, Major Tucker (114) invented the hot-wire microphone, the details of which remained secret until after the War. The principle was then applied to medicine: Heald and Tucker (58) used the hot-wire microphone to record the "body rebound" caused by the heart beat, and, in 1920, A. V. Hill (64) (65) published a preliminary description of a hot-wire sphygmograph.

In 1922, Bramwell and Hill (13) (14) reinvestigated the work of Roy on the relationship between internal pressure and extensibility in portions of excised carotid artery. They showed that the original formula of Moens might be simplified to an even greater extent than had been suggested by Grunmach. According to Bramwell and Hill, the relationship between the pulse-wave velocity and extensibility could be expressed by the equation:

$$V(\text{velocity in metres per second}) = \frac{3.57}{\sqrt{\% \text{ increase in volume per mm. Hg. increase in pressure.}}}$$

A direct observation of the velocity of the pulse wave in any segment of an artery thus enables the mean extensibility of the vessel under consideration to be calculated in absolute units.

The equation then becomes:

$$\begin{array}{l} \text{Extensibility} \\ (\% \text{ increase in volume per} \\ \text{mm. Hg. rise in pressure}) \end{array} = \left[ \frac{3.57}{v} \right]^2$$

The hot-wire was applied to this investigation a year later by Bramwell, Downing and Hill (12), and the results confirmed.

In 1923, Bramwell, Hill and McSwiney (16) applied the hot-wire sphygmograph to the estimation of pulse-wave velocity in the living subject, and obtained records from a number of normal subjects of varying ages. These observers established a relationship between age and pulse-wave velocity as estimated between carotid and radial pulses. Using the formula suggested by Bramwell and Hill, it was shown that with increasing age there was a progressive diminution of the extensibility of the arteries in the carotid-radial system.

The relation between pressure and pulse-wave velocity in the living subject has been investigated by Bramwell, McDowall and McSwiney (17). By placing a broad sphygmomanometer bandage of known width round the arm and inflating it to various pressures, these observers were able to alter the "effective pressure" in the portion of artery under the bandage, this being estimated as equal to the diastolic pressure of the subject minus the "applied pressure" (i.e. in the bandage). The pulse-wave velocity between carotid and radial pulses was estimated by the hot-wire method at various "effective pressures" up to and including the diastolic pressure, and from this the pulse-wave velocity in the section of artery under the bandage was calculated.

This work was confirmed in 1928 by Hemingway, McSwiney and Allison (60), and further investigations were carried out by employing a negative pressure armlet and so obtaining "effective pressures" greater than the diastolic pressure of the individual.

From the survey of the literature, it is clear that while considerable attention has been paid to the velocity of the pulse wave in the arterial system, little notice has been taken of the varying extensibility of the different arteries. Weber, as may be seen, estimated the velocity of the pulse wave in 1834. Some fifty years later, Roy established the relationship between internal pressure and extensibility, and Moens related extensibility to pulse-wave velocity. These three observers laid the foundations of our knowledge of the function of the arteries, and subsequent investigation has been directed primarily to obtaining greater accuracy by effecting improvements in the technique, and to a study of the alterations in pulse-wave velocity associated with various pathological conditions. The carotid and radial pulses being readily accessible, the rate of transmission of the pulse wave between these two points has been selected by most observers as the standard, and their findings based on this measurement. It is true that Bazett and Dreyer in their investigations suggested that the pulse-wave velocity was lower in the brachial than in the radial artery.

These observers were, however, more interested in the relationship of pulse-wave velocity to arterial pressure, and no survey was made of the relationship of the rate of propagation of the pulse wave to different arteries.

Moens, it would appear, was of opinion that the arteries were of uniform structure, and he attempted to reduce the equation to one of pure physics, varying with the alteration in calibre and thickness of the vessel wall.

Härthle (70), in 1923, showed that the femoral artery is normally less extensible than the carotid artery. This observer investigated the relation between internal pressure and volumetric expansion in living animals by applying a plethysmograph. By applying to his results a physical formula which took into account the diameter and thickness of the vessel wall, Härthle showed that there was a progressive decrease in the extensibility of the vessels in the arterial path. As Hepner (61) had previously shown that throughout the arterial tree the thickness of the arterial wall varies directly



as the transverse section, Hürthle argued that this variation must be due to some other factor.

From histological observations it is known that there is considerable variation in the structure of the arteries, and it seemed important to correlate these factors where possible with the extensibility of the vessel wall. This was one of the objects which prompted this investigation.

The technique of the hot-wire method of estimating pulse-wave velocity has been revised, and all sources of error have, as far as possible, been eliminated.

A method has been devised whereby accurate measurements of the pulse-wave velocity can be made in the brachial and in the radial artery: a similar technique has also been evolved for the lower limb.

The effect on the pulse-wave velocity of various physiological processes has been examined, and the relationship between pulse-wave velocity and age has been investigated in a series of over one hundred normal individuals of ages ranging from

five to eighty years.

The histological structure of the arteries has also been examined, and a correlation has been found between structure and pulse-wave velocity in different arteries.

A rigid endeavour has been made to limit the investigation to normal subjects, in order that definite data might be available for future work. No subjects in whom any evidence of arterial or circulatory disease was detected are included in the results.

The majority of the subjects were students, members of the University Staff and workmen of various trades engaged in the extension of the Medical School at Leeds. For subjects under the age of sixteen years, school children were available and an equal number of male and female children were investigated.

Although no abnormal subjects are reported, it is of interest to note that several have been encountered in the course of this investigation. The number investigated, however, does not justify any conclusions being drawn, but the conditions



found in these cases, when examined in conjunction with the results obtained from normal subjects, suggest that an investigation of the extensibility of the arteries in various pathological conditions would yield information of undoubted value to the clinician.

VOLUME ONE

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SECTION

TWO

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## M E T H O D

### THE PRINCIPLE AND ITS APPLICATION

#### INSTRUMENTS:

Galvanometers.

Source of illumination.

Time-marker.

Wheatstone bridge.

Hot-wire container.

Connecting Tubes.

Receivers:

(a) Carotid (d) Femoral

(b) Brachial (e) Popliteal

(c) Radial (f) Dorsalis Pedis

(g) Arrangement for respiratory records.

Measuring machine.

#### METHOD OF TAKING RECORDS:

General arrangement of room.

Records from the arm.

Records from the leg.

Anatomical measurements.

Estimations of blood pressure.

## M E T H O D

Electrically heated platinum as a sensitive detector of air movement has been used for some years, G. A. Shakespeare having applied this method in 1902 to determine wind velocity.

The fact that platinum, on account of its spongy texture, has the relatively enormous surface of 3,600 sq. cm. per cc. of metal allows cooling to take place in a piece of electrically heated platinum wire at an extremely rapid rate when the wire is subjected to a current of air; quite a small current of air is sufficient to cause a considerable fall in the temperature of the wire. The cooling so produced causes a change of the electrical resistance of the wire, which, if connected through an appropriate circuit, may be recorded by means of a string galvanometer.

The circuit is connected in the form of a Wheatstone bridge, two arms being made up by a spiral ratio resistance,  $R_1$ ,  $R_2$ , the third arm by a known resistance  $R_3$ , and the fourth arm by the hot

wire. A dial shunt is provided to enable adjustments to be made of the current passing through the galvanometer circuit. A simple diagram of the circuit is given in Fig. I.

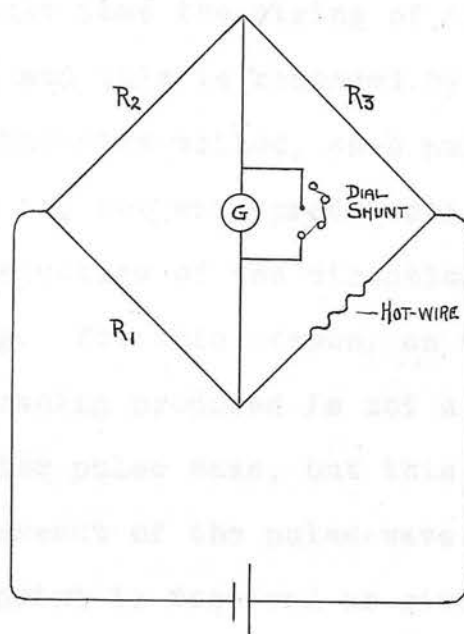


FIG. I.

By employing a Wheatstone bridge, it will be seen that if the balance be upset by the cooling of the hot wire, a current will flow through the galvanometer circuit and so produce a deflection of the fibre which may be recorded photographically.

In practice, a suitable receiver is placed over an artery and connected to a rubber tube so arranged that the hot wire is interposed across its lumen. Each wave produced in the rubber tube by the pulsations of the artery cools the hot wire, with the result that the string of the galvanometer is deflected and this is recorded by the camera.

In the hot-wire method, each puff of air passing over the hot wire produces a cooling effect, irrespective of the direction in which it is travelling. For this reason, as will be seen later, the tracing produced is not a true record of the form of the pulse wave, but this is unimportant as for measurement of the pulse-wave velocity only the initial point is required as given by the sharp upstroke.

In these investigations the hot-wire method has been used exclusively for the following reasons:

- (a) Friction is eliminated, and inertia forces are reduced to a minimum.
- (b) The sharp upstroke obtained on the records enables accurate measurements to be made.

- (c) Records may be obtained, using various types of receivers (cup, tambour, pressure bandage, etc.) with equal facility.
- (d) A double fibre case, or two string galvanometers, may conveniently be used, and so records from two or three sites may be recorded simultaneously.
- (e) The arrangement of the instrument, once set up, even for three simultaneous records, is permanent and requires little adjustment.

### INSTRUMENTS.

#### Galvanometers.

In the original experiments an Einthoven string galvanometer, as supplied by the Cambridge & Paul Instrument Company, was used. A double fibre case was employed, containing a pair of 12 micron copper strings with a resistance of about 1,000 Ohms each. When it was desired to use three strings

simultaneously, a single fibre case was mounted with a glass fibre, having a resistance of about 4,000 Ohms. The eye piece of the galvanometer was then removed, and a second galvanometer placed immediately in front. This second instrument was a small string galvanometer designed by Salamonson and contained two 11 micron copper strings of low resistance. The eye piece of the small instrument acted in place of the one removed from the large instrument, and the images of all three fibres were focussed at the same time. In this way, three separate phenomena could be simultaneously recorded.

#### Source of Illumination.

The beam of light was supplied by a Pointolite lamp, as manufactured by the Cambridge & Paul Instrument Company. When both galvanometers were in use, they were so placed in series that the single beam of light traversed both instruments.



### Time-Marker.

The time-marker consisted of an electro-magnetically-driven vibrating bar standardised to give fifty vibrations per second, and a motor with a spoked disc so arranged that the spokes intercepted the beam of light while rotating, the light being cut off twenty-five times per second.

The time-marker was calibrated at intervals by comparison with a tuning fork or by running off a length of paper and exposing it for a definite period with the aid of an accurate stop-watch, the number of time intervals recorded being subsequently counted on the paper. Adjustment is made by altering the position of the weight on the end of the vibrating bar.

As the accuracy of the results depended largely on the timing mechanism, the instrument was calibrated frequently during the experimental work.

### Wheatstone Bridge.

The instruments forming the bridge were mounted on a separate table for convenience in arranging the position of the subject and the

mounting of the instruments.

A dial shunt was provided for the galvanometer circuit in order that the amount of current passing through it might be easily controlled. A spiral ratio resistance of about 60 Ohms was used to form two arms of the bridge, while the third and fourth arms of the bridge were made up by a fixed wound resistance and the hot wire respectively. The resistance of the former was arranged to be about equal to that of the hot wire (30 Ohms.).

Current was supplied from several two volt accumulators connected in series, and it was found that four accumulators (8 volts) sufficed to bring the wire to the required heat.

#### Hot-Wire Container.

The type of container used was that described by Bramwell, Hill and McSwiney (16), consisting of two brass sleeves separated from one another by a small cylinder of vulcanite or other non-conducting material. The ends of the brass sleeves were designed to fit tightly into the thick rubber connecting tubes, and each sleeve was provided

# HOT-WIRE CONTAINER.

( ACTUAL SIZE )

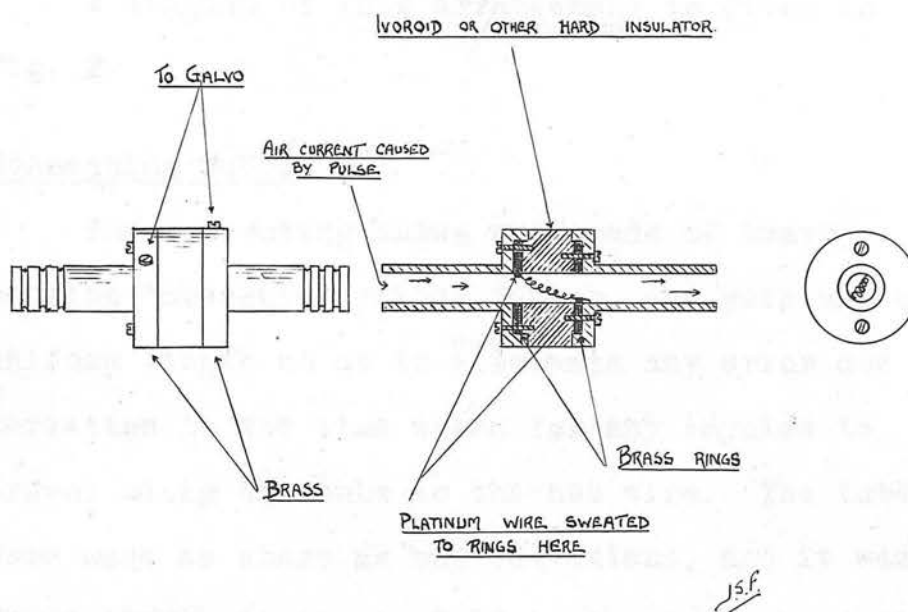


FIG. 2.

with a terminal. A piece of 11 micron platinum wire of about 30 Ohms resistance was passed through the vulcanite cylinder and connected to each sleeve. The whole was made perfectly airtight by covering with paraffin wax after assembly.

A diagram of this arrangement is given in Fig. 2.

#### Connecting Tubes.

The connecting tubes were made of heavy section "pressure" rubber tubing, and were all of uniform length so as to eliminate any error due to variation in the time taken for any impulse to travel along the tube to the hot wire. The tubes were made as short as was convenient, and it was found that a distance of 18 inches between receiver and hot wire permitted ease in manipulation.

#### Receivers.

The receivers naturally varied with the point from which it was desired to obtain a record.

- (a) Carotid: For carotid tracings a small glass funnel, 2 cm. in diameter, was used. The end of the rubber tube beyond the hot wire

was left open to avoid obstructing the current of air in the tube.

- (b) Brachial: For records from the brachial artery, a hollow rubber bandage, 2 cm. broad, was strapped round the arm just above the elbow and connected to a Pachon oscillometer; the bandage was then inflated by the pump of the Pachon to a pressure not exceeding 40 mm. Hg. The use of the oscillometer enabled a definite pressure to be applied, and provided an adequate reservoir for air to flow past the hot wire. It was found essential that the whole of this system should be air-tight, otherwise in addition to an effect due to change of pressure, the escape of air affected the hot wire and disturbed the records. Care was also taken to ensure that the pressure applied was as low as possible and certainly, in no circumstances, greater than 40 mm. Hg. The importance of this will be discussed later.

- (c) Radial: The receiver used for the radial artery was the tambour and spring button, manufactured by Jacques as a radial pulse recorder. It is sensitive and gives a definite point on the artery for measurement purposes.
- (d) Femoral: The tracings from the femoral artery were taken by a tambour similar to that used for the radial artery, but held in place by means of an inguinal hernia truss. The tambour was fixed to the pad of the truss by a small adjustable steel arm, so arranged that the position of the tambour could be altered in relation to the pad of the truss. The adaptation of a truss for this purpose enabled the receiver to be held firmly, and as the pad of the truss rested in the usual place over the inguinal canal, no pressure was exerted on the artery beyond that of the lightly applied tambour.

- (e) Popliteal: Tracings from the popliteal artery were obtained by a small rubber ball, 2 cm. in diameter, inflated through the connecting tube by a Pachon oscillogram. The rubber ball was adjusted so that it lay directly over the popliteal artery, and retained in this position by a broad leather strap.
- (f) Dorsalis Pedis: A hollow rubber ball, 2 cm. in diameter, was also used for records from the Dorsalis Pedis artery, the retaining strap being fixed round the ankle, and the ball inflated by the Pachon oscillogram to a pressure of 30 or 40 mm. Hg.
- (g) Arrangement for Respiratory Record: A small cylindrical drum about three inches long and one and a half inches in diameter with rubber ends was strapped round the chest, the straps being fixed to the centres of the rubber diaphragms. Inspiration thus produced a negative pressure in the drum, which, in turn, was connected by means of



a rubber tube to a small tambour placed in front of the camera: this operated an arm moving across the field of light, producing an image on the camera face.

The various receivers are illustrated in Figs. 3 to 9.

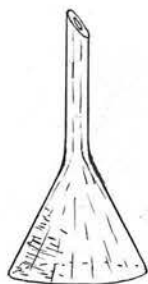


FIG. 3. GLASS FUNNEL USED AS CAROTID RECEIVER

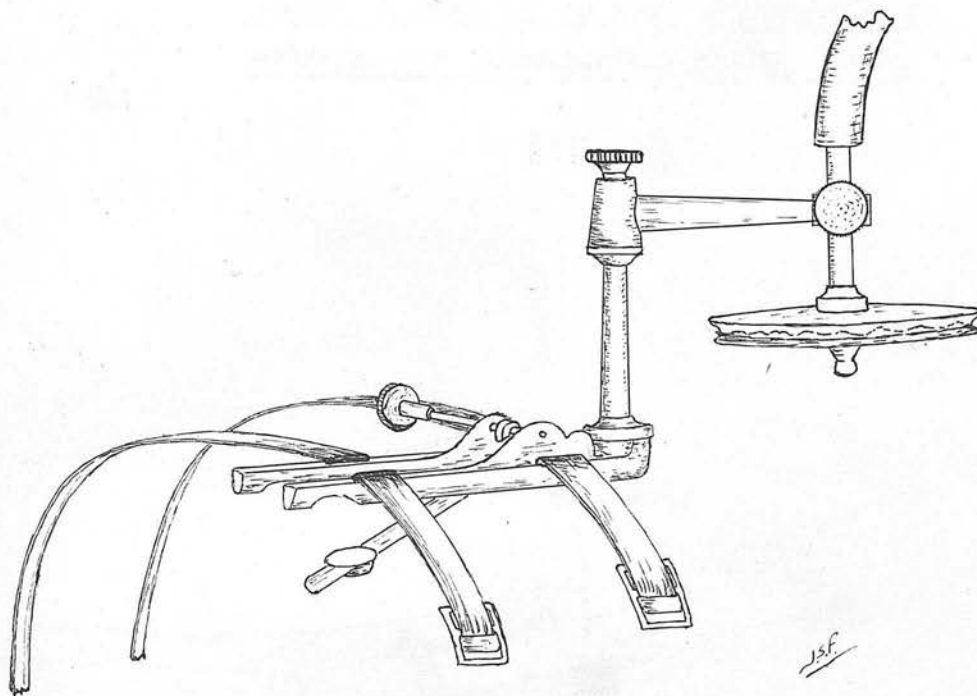
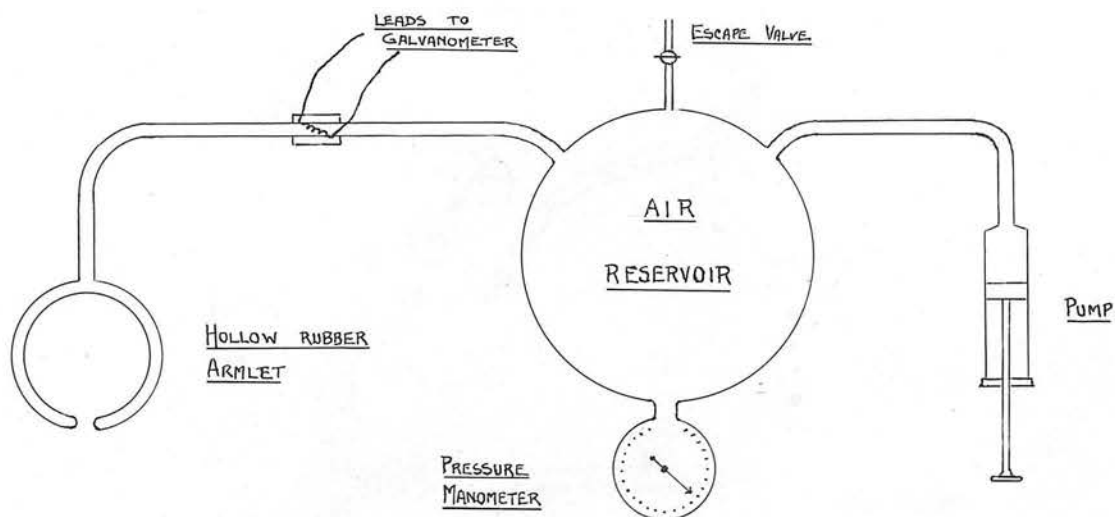


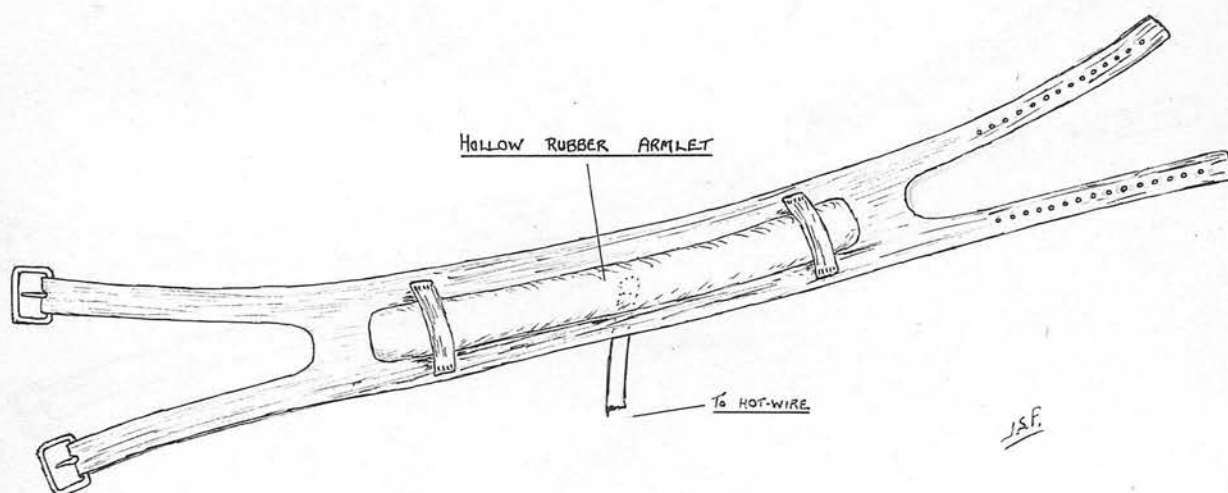
FIG. 4. JACQUET RADIAL PULSE RECEIVER



THE AIR RESERVOIR IS NECESSARY IN ORDER THAT THERE MAY BE FREE PASSAGE OF AIR ACROSS THE HOT-WIRE.

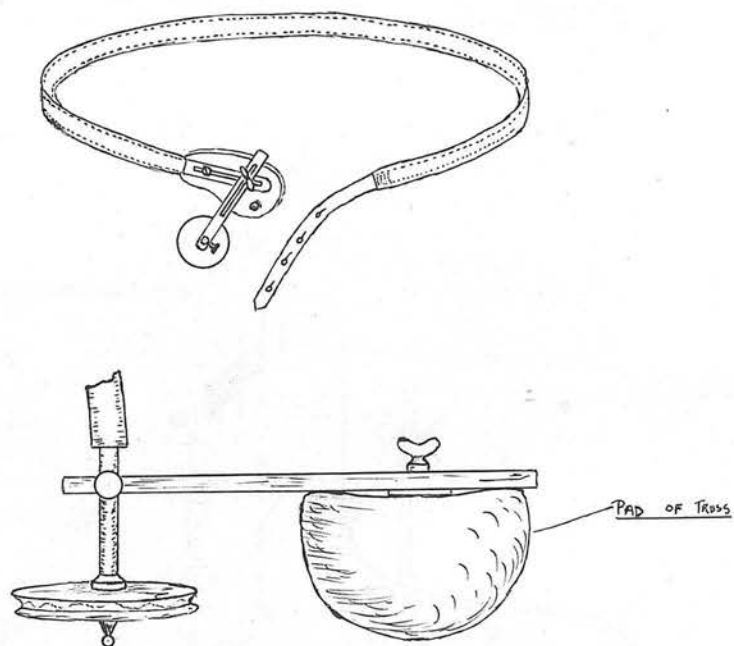
DIAGRAM ILLUSTRATING GENERAL ARRANGEMENT OF APPARATUS FOR RECORDS FROM BRACHIAL ARTERY.

FIG. 5.



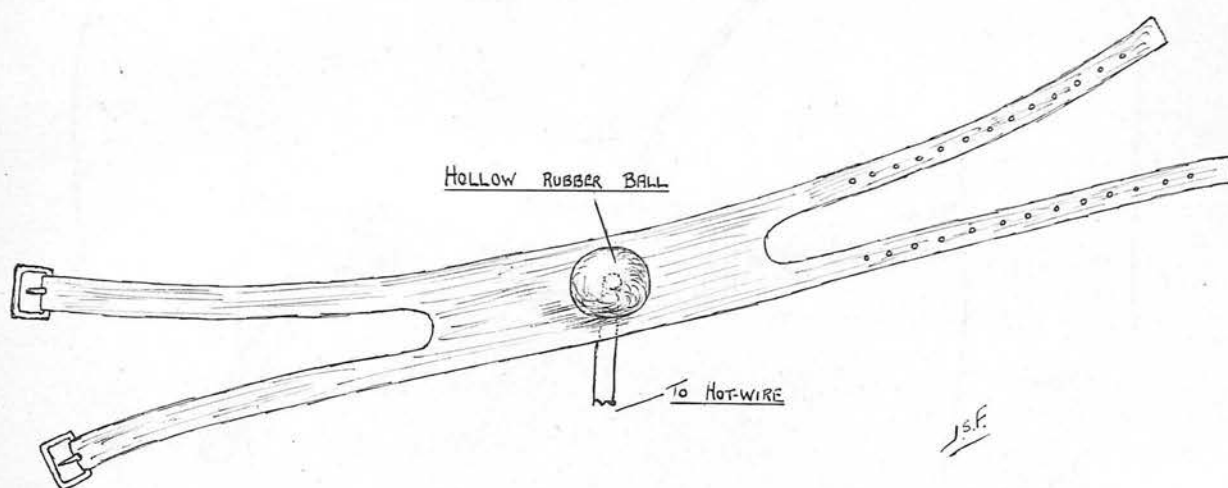
RECEIVER FOR BRACHIAL ARTERY

FIG. 6.



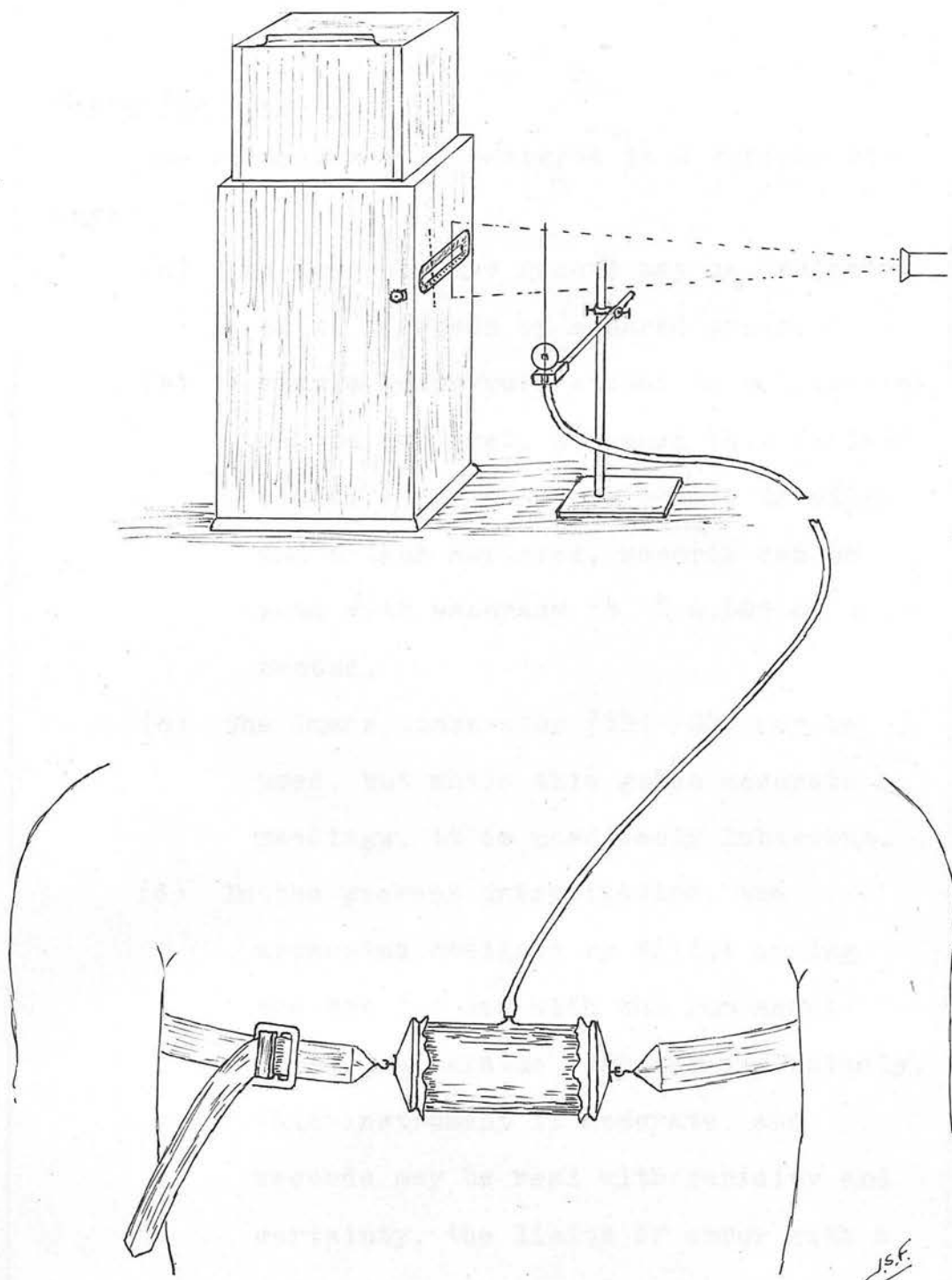
RECEIVER FOR FEMORAL ARTERY

FIG. 7.



RECEIVER FOR POPLITEAL AND DORSALIS PEDIS ARTERY

FIG. 8.

GENERAL ARRANGEMENT FOR RESPIRATORY RECORDSFIG. 9.

### Measuring Machine.

The records may be measured in a variety of ways:

- (a) The image of the record may be projected on to a screen of squared paper.
- (b) A simple glass rule etched in millimetres may be employed, and when this is laid etched side downwards on the tracing, and a lens employed, records can be read with accuracy to  $\pm 0.005$  of a second.
- (c) The Lucas Comparator (83) (82) may be used, but while this gives accurate readings, it is needlessly laborious.
- (d) In the present investigation, the apparatus designed by Elliot during the War for use with the gun-sound-ranging apparatus was used exclusively. This instrument is accurate, and records may be read with rapidity and certainty, the limits of error with a

suitable tracing which gave sharp deflections being  $\pm 0.001$  of a second. The instrument was supplied by the Cambridge & Paul Instrument Company.

#### METHOD OF TAKING RECORDS.

A photograph of the room in which the experiments were conducted is given in Fig. 10, and from this a general idea may be obtained of the manner in which the various instruments were arranged. The subject was seated comfortably in an easy chair in a semi-reclining posture close to the small table on which the hot wires were arranged.



PHOTOGRAPH SHOWING GENERAL ARRANGEMENT OF ROOM.

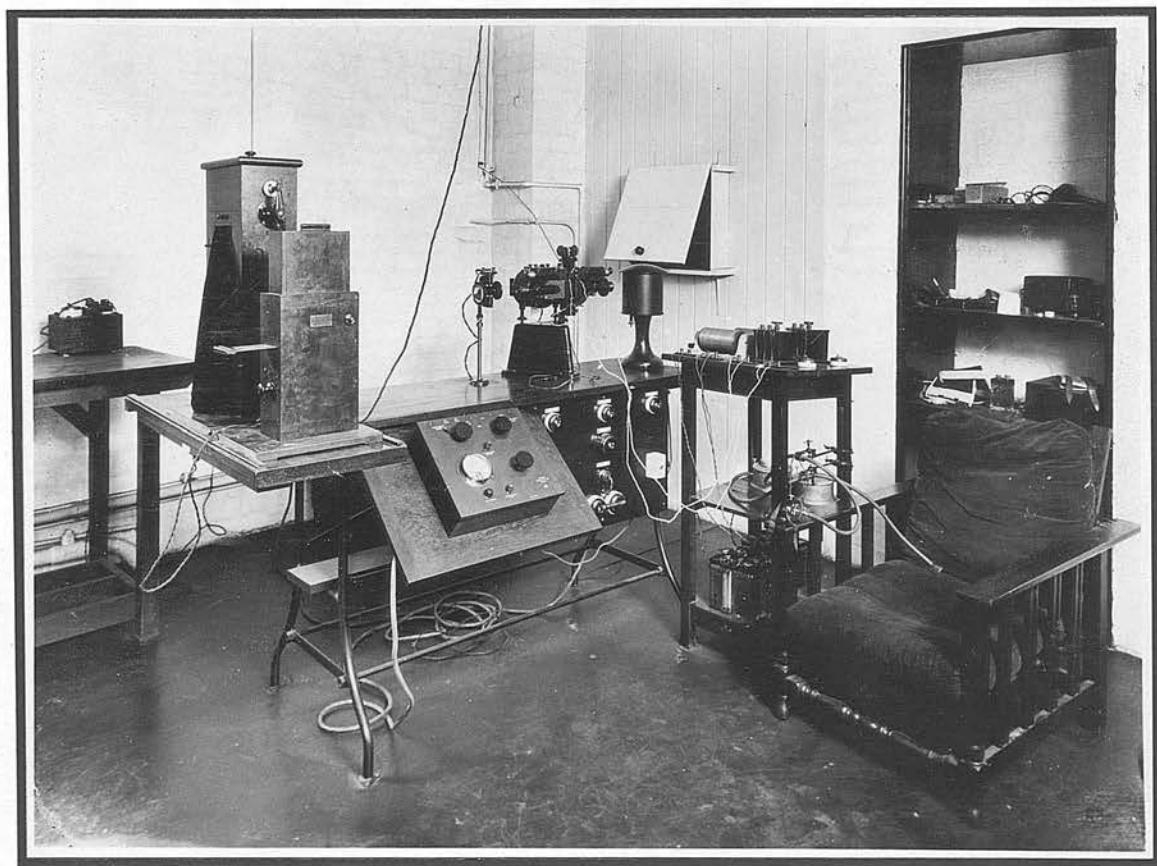


Fig. 10.

### Records from the Arm.

In taking records from the arm, the right limb was used and was allowed to rest on the side of the chair in such a position that it lay horizontally at about the same level as the heart.

The position of the radial artery was marked on the surface of the arm with a skin pencil where the impulse was most pronounced, and the radial tambour fixed over this point. The hollow rubber bandage was then applied round the arm immediately above the elbow and inflated by the Pachon pump to a pressure not exceeding 40 mm. Hg.

Some observers have devised methods whereby the carotid receiver is held in position by straps, etc., but as no difficulty was experienced in obtaining impulses from this region, the point of maximum impulse was simply marked on the skin, and the small glass cup held over the carotid artery while the record was being taken.

The camera motor switch was so arranged that it could conveniently be operated by the person holding the carotid cup in position; no assistant,

therefore, being necessary.

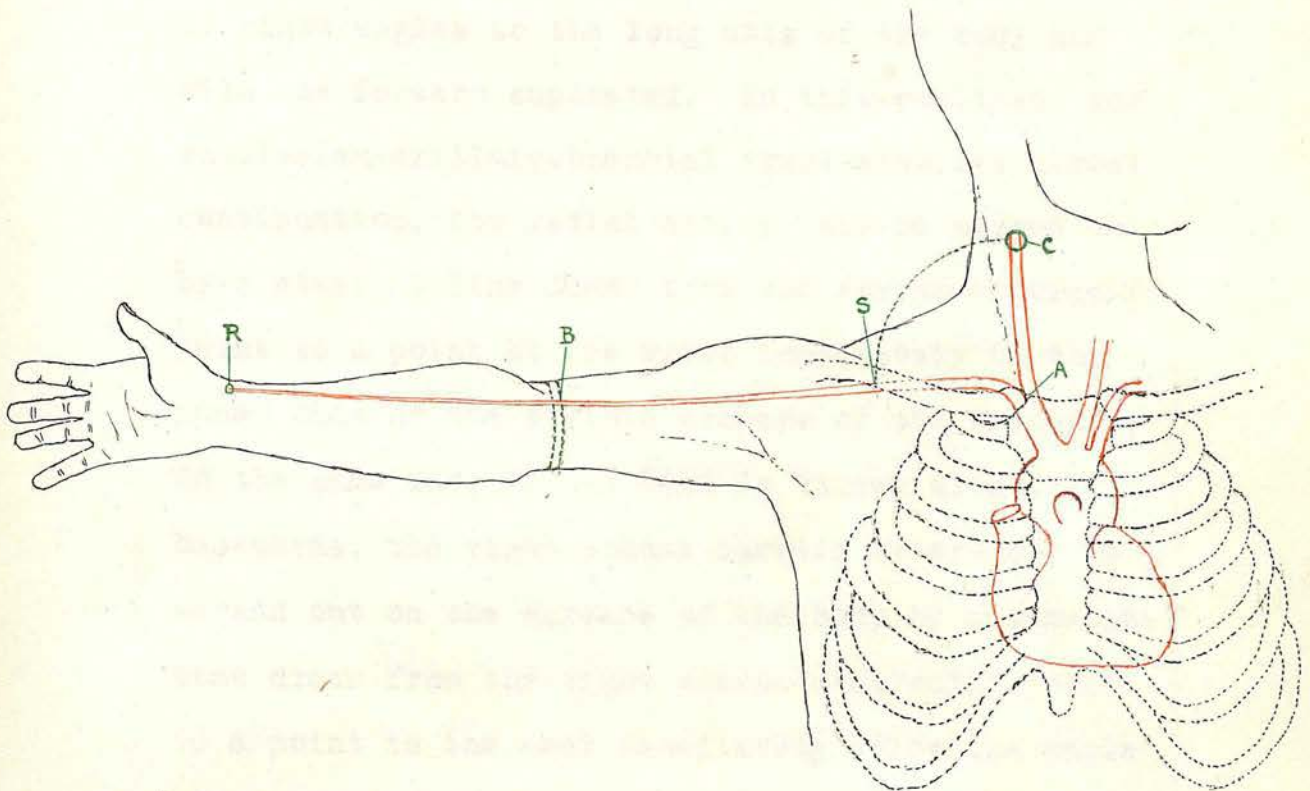
In each case some fifteen impulses were recorded, from which it was usually possible to make a selection for measurement.

#### Records from the Leg.

In taking records from the leg, the truss was applied with the subject in the erect posture. A reclining posture in the chair was then assumed as before, and the limb was supported horizontally on another chair. The recording tambour was then fixed to the pad of the truss and swung into position over the point of maximum impulse of the femoral artery.

One rubber ball receiver was then applied to the popliteal artery at the level of the medial condyle of the femur, and the other receiver of this type was fixed over the dorsalis pedis artery. Both receivers were then inflated to a pressure not exceeding 40 mm. Hg., and, as in the arm, some fifteen impulses were recorded.

DIAGRAM SHOWING MEASUREMENT POINTS  
IN  
THE ARM.



MEASUREMENTS ARE TAKEN BETWEEN

A AND C

A AND B

A AND R

THE WAVE IS ASSUMED TO REACH THE POINTS S & C SIMULTANEOUSLY, S AND C BEING EQUIDISTANT FROM A. THUS THE TIME INTERVAL BETWEEN THE IMPULSES AT C AND B REPRESENTS THE TIME TAKEN BY THE PULSE-WAVE IN TRAVERSING THE SECTION OF ARTERY SB, THE LENGTH OF WHICH IS EQUAL TO THE DISTANCE AB MINUS THE DISTANCE AC.

FIG. II.

### Anatomical Measurements.

In measuring the upper limb, the subject was made to stand erect with arm extended to the side at right angles to the long axis of the body and with the forearm supinated. In this position, the subclavian-axillary-brachial trunk with its direct continuation, the radial artery, may be mapped out by a straight line drawn from the sterno-clavicular joint to a point at the wrist immediately to the inner side of the styloid process of the radius. In the same way, if the head is thrown slightly backwards, the right common carotid artery may be marked out on the surface of the body by a straight line drawn from the right sterno-clavicular joint to a point in the neck immediately below the angle of the jaw, where the pulsation can be felt with the finger.

In the upper limb, three measurements were taken:

- (1) Sterno-clavicular joint to the centre of the point of application of the carotid cup.

- (2) Sterno-clavicular joint to the upper border of the hollow rubber bandage applied at the elbow.
- (3) Sterno-clavicular joint to the point from which the record from the radial artery was taken.

These points are illustrated in Fig. 11.

For the purposes of this investigation, it is estimated that the pulse wave velocity in the carotid artery from behind the sterno-clavicular joint upwards will be the same as that for a corresponding distance from behind the sterno-clavicular joint along the subclavian-axillary trunk. Hence, by subtracting the measurement between the sterno-clavicular joint and the carotid from the measurements along the subclavian-axillary trunk, it is possible to calculate the length of artery traversed by the pulse wave during the time interval under consideration.

It is realised that the innominate artery may not always divide into its two terminal branches immediately behind the sterno-clavicular joint.



Furthermore, since the horizontal extent of this articulation is considerable, the measurement in each case was taken from the mid point of the sternal end of the clavicle.

In the lower limb, measurements were taken from the point of application of the femoral artery receiver, along the inner aspect of the thigh to a point immediately behind the medial condyle of the femur on a level with the centre of the rubber ball receiver. From there a further measurement was taken along the inner side of the leg to the centre of the rubber ball receiver over the dorsalis pedis artery.

#### Estimation of Blood Pressure.

Considerable difference of opinion exists with regard to the interpretation of the various phenomena associated both with the oscillatory and with the auscultatory method of estimating the blood pressure. The subject was investigated in 1916 by Brooks and Luckhardt ( 20 ) and since then has been very fully examined by Erlanger ( 32-36 ). In the present investigation, Erlanger's view has



been adopted, and the pressure at which the sharp sounds alter and become dull in character is accepted as equivalent to the diastolic pressure.

In each case the blood pressure was estimated immediately after the experiment, the sphygmomanometer bandage being applied in the case of the arm above the elbow, and in the case of the leg above the knee.

### INTERPRETATION OF RECORDS.

#### Physical Considerations.

As a result of the physical principle involved, the records obtained with the hot-wire method differ in form from those given by other sphygmographs. First, since cooling of the wire may be produced by a current of air passing through the tube in either direction, both expansion and contraction of the vessel under the receiver give rise to similar deflections in the hot-wire record. Secondly, heat is being liberated continuously in the wire by the current passing in it, and this heat is dispersed by conduction, convection and radiation. The temperature of the wire, therefore,

remains high and constant until a sudden passage of air cools it. When the passage of air has ceased, the wire rapidly warms again. As a result of this, the plateau of sustained pressure, which is represented on an ordinary pulse tracing of the carotid, is replaced in the hot-wire record by two rapid deflections with sharp peaks. These peaks correspond to the rise in pressure immediately preceding the commencement of the plateau and the fall in pressure immediately following it, whereas during the plateau itself, the heating of the wire being unopposed, the galvanometer returns to the zero position.

Fig. 12 shows a carotid tracing obtained by an optical method (Wiggers Capsule). This shows the usual form of the pulse wave.

Fig. 13 shows a hot-wire record obtained from the same subject a few minutes later. The rapidity of the "take-off" in the hot-wire record is at once apparent.

OPTICAL RECORD OF CAROTID ARTERY  
obtained by Wigger's capsule.

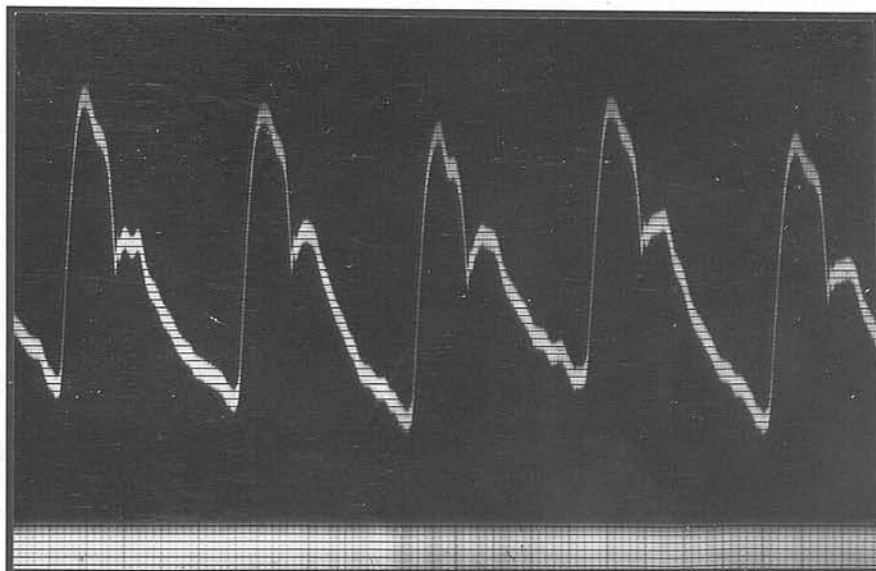


Fig. 12.

HOT-WIRE RECORD OF CAROTID ARTERY  
(same case as above)  
Note sharp "take off" of hot-wire record.

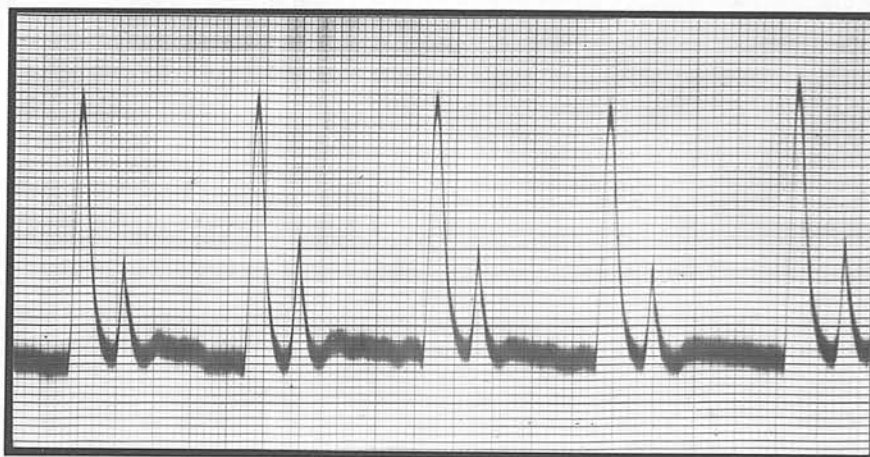


Fig. 13.

Time intervals 0.04 of a second.

In order to investigate this subject further, an attempt was made to record the impulse simultaneously on the same photographic plate by the two methods. The difficulty in doing this lies in the fact that, in the case of the Wiggers capsule, an air-tight system is required, while, with the hot-wire method, provision must be made for the free passage of air to and from across the wire, either by having the end of the connecting tube beyond the hot wire open or attached to a reservoir, e.g. Pachon oscillometer. Any attempt to compromise in a common system results in a distortion of one or both records, as may be seen in Fig. 14.



SIMULTANEOUS OPTICAL AND HOT-WIRE RECORD  
of  
CAROTID ARTERY

showing distortion produced  
by  
leak of air in optical system  
and  
obstruction to passage of air over hot-wire.



Fig. 14.

Upper tracing.....Optical record.

Lower tracing.....Hot-wire record.

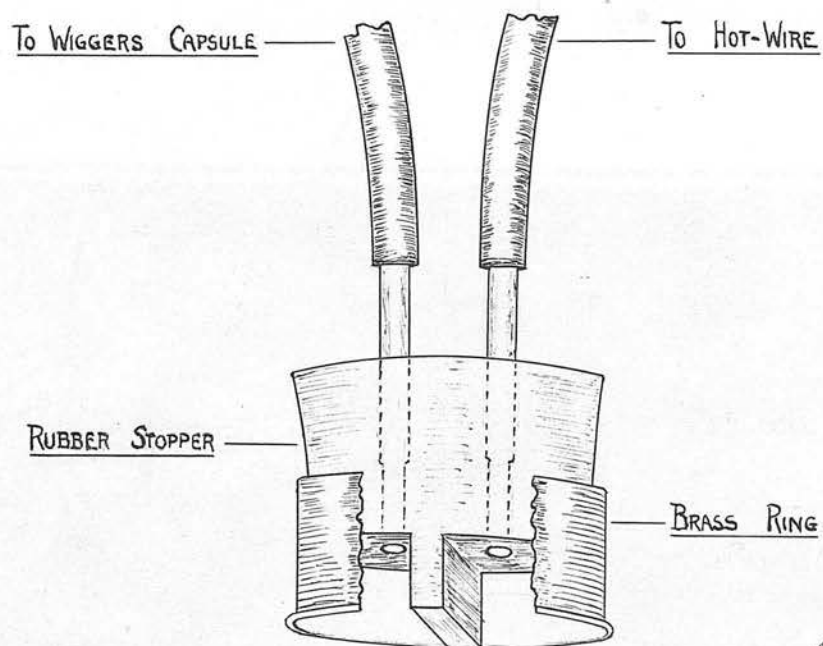
Time intervals      0.04 of a second.

A receiver was accordingly devised by partially sectioning a rubber cork and fitting it into a brass ring as shown in Fig. 15. When this was applied to the carotid, two separate but simultaneous impulses were obtained which were transmitted by tubes of equal length to the two recorders. It was possible thus to have the Wiggers capsule system air-tight, while the hot-wire system was left open.

An example of a tracing so obtained is given in Fig. 16, which makes it possible to compare accurately the two methods of recording.

RECEIVER FOR SIMULTANEOUS RECORDS

FROM

WIGGER'S CAPSULE AND HOT-WIREFIG. 15.



SIMULTANEOUS OPTICAL AND HOT-WIRE RECORD  
of  
CAROTID ARTERY.

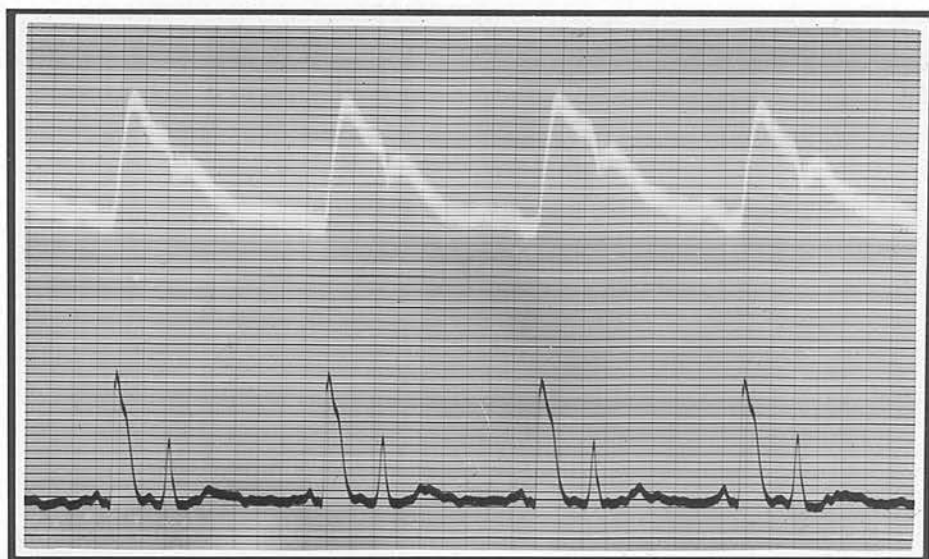


Fig. 16.

Upper tracing.....Optical record.

Lower tracing.....Hot-wire record.

Time intervals.....0.1 of a second.

It will be at once apparent that the hot-wire method gives no direct evidence as to the absolute value of the pressure or of the movement of the artery, and its usefulness depends primarily on the speed with which it is capable of acting.

#### Typical Records.

Examples of typical tracings are shown in Figs. 17 to 30. Records obtained in the arm and in the leg, both with two strings and with three strings in simultaneous use, are reproduced. Records showing respiratory tracings are also given. The tracings shown are portions cut from actual records obtained, and thus indicate the size of tracings available for measurement.

RECORDS FROM ARM USING TWO STRINGS SIMULTANEOUSLY.

(Paper moving at 8 cms. per second).  
Time intervals 0.2 of a second.

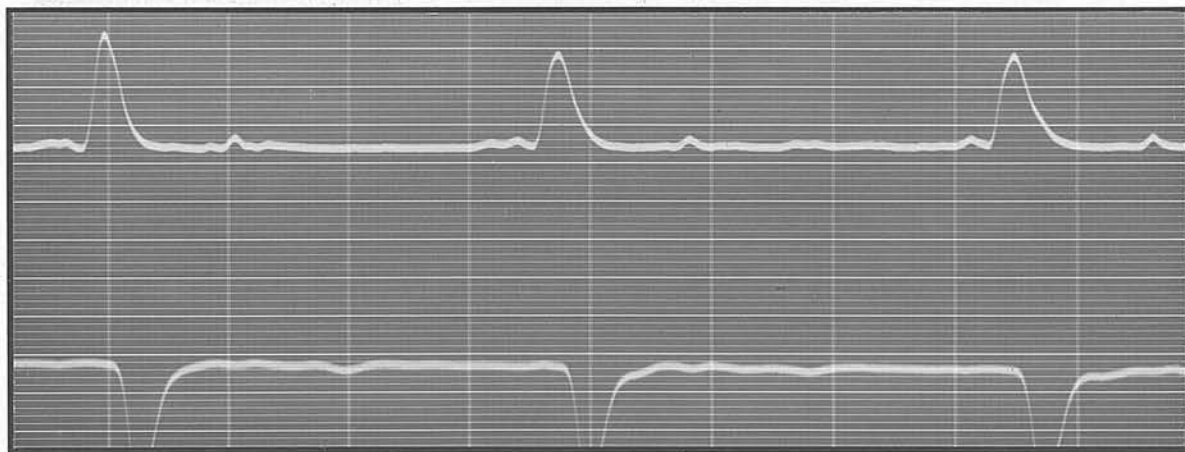


Fig. 17. CAROTID - BRACHIAL (Brachial artery).

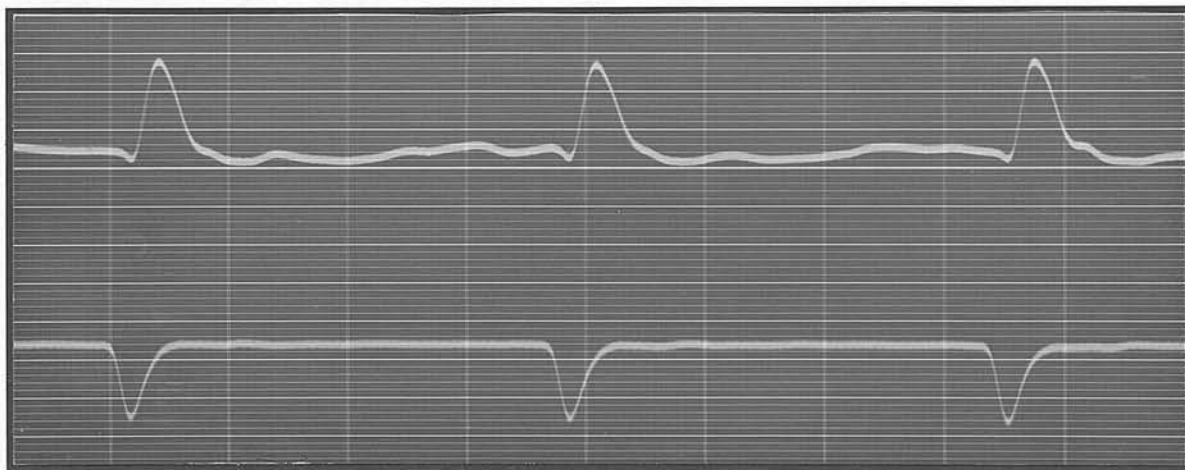


Fig. 18. BRACHIO - RADIAL (Radial artery).

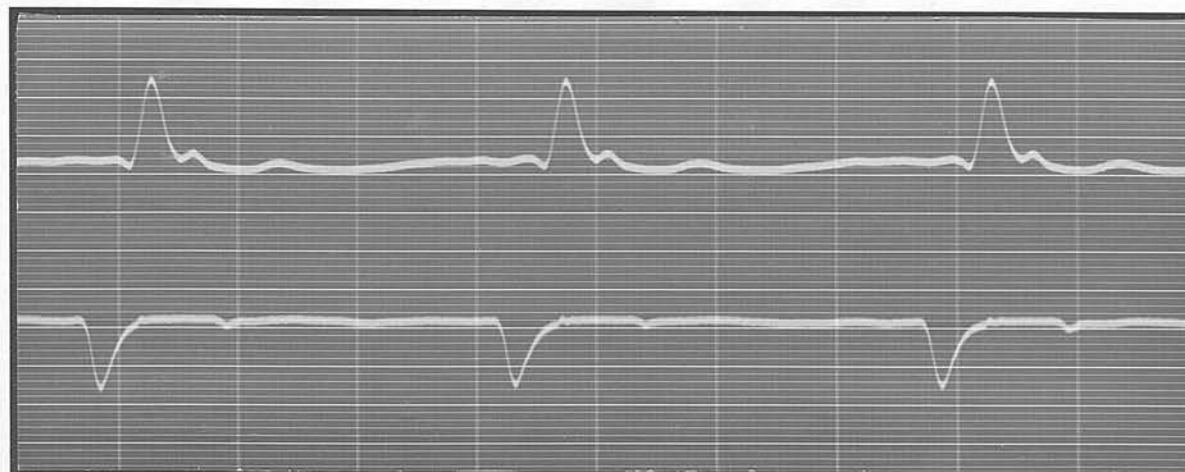


Fig. 19. CAROTID - RADIAL (Whole arm).

RECORDS FROM THE ARM USING TWO STRINGS SIMULTANEOUSLY.

Paper moving at 11.5 cms. per second.  
Time intervals 0.04 of a second.

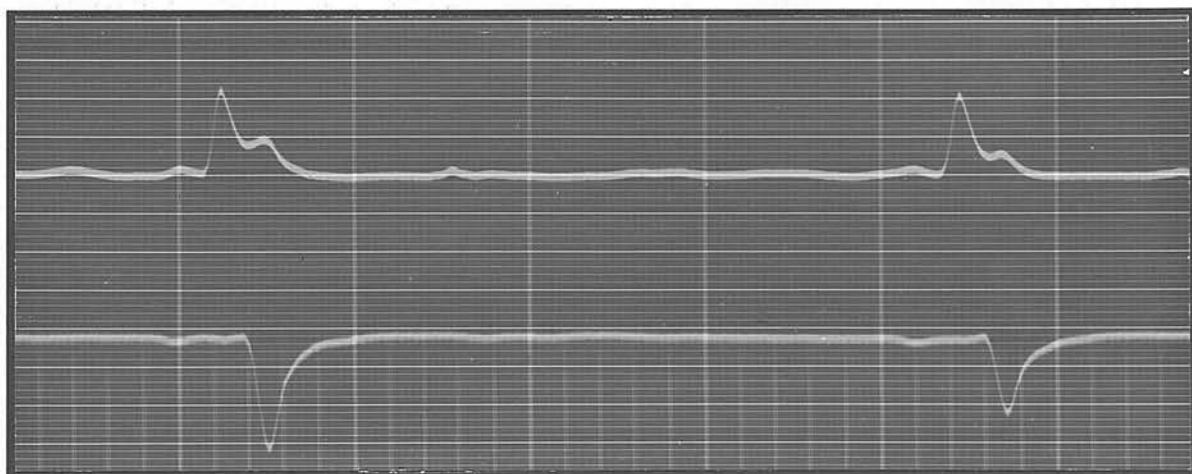


Fig. 20. CAROTID - BRACHIAL (Brachial artery).

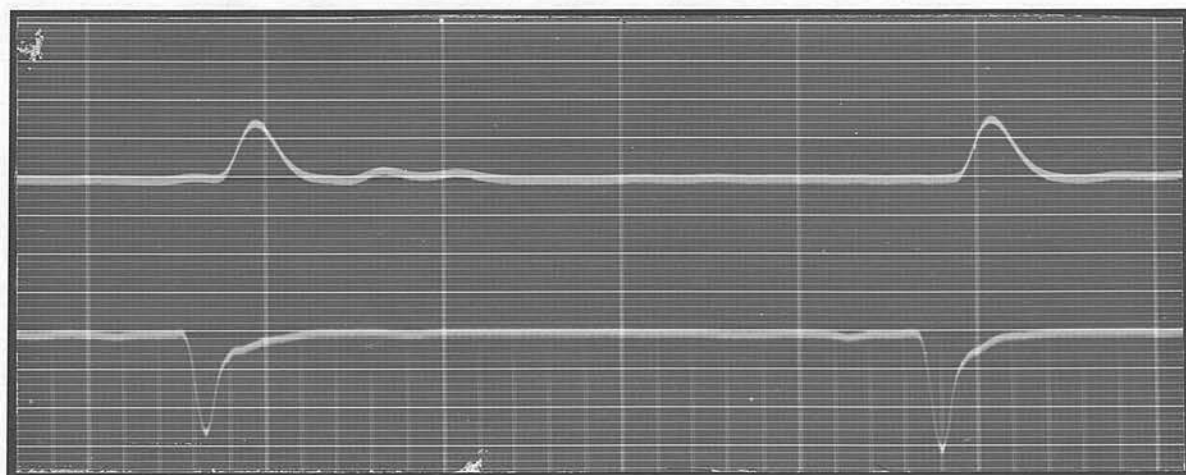


Fig. 21. BRACHIO - RADIAL (Radial artery).

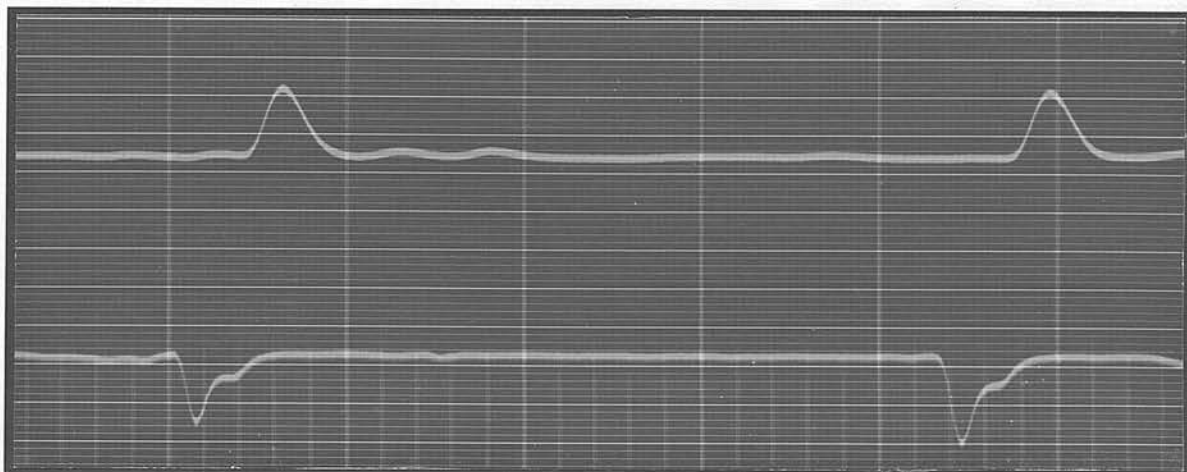


Fig. 22. CAROTID - RADIAL (Whole arm).

RECORDS FROM THE ARM USING TWO STRINGS SIMULTANEOUSLY.

RESPIRATORY RECORD - Inspiration up.  
Time intervals 0.04 of a second.

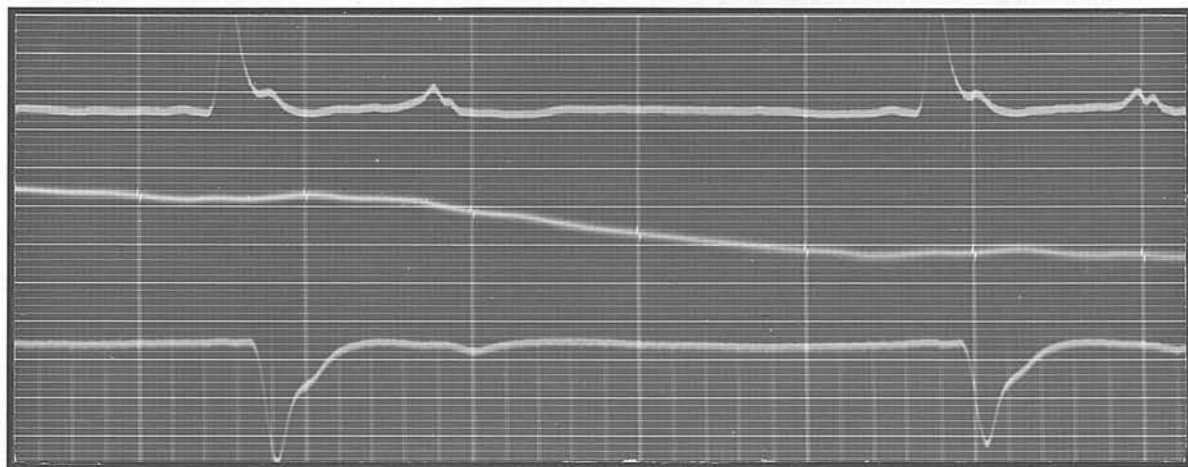


Fig. 23. CAROTID - BRACHIAL (Brachial artery).

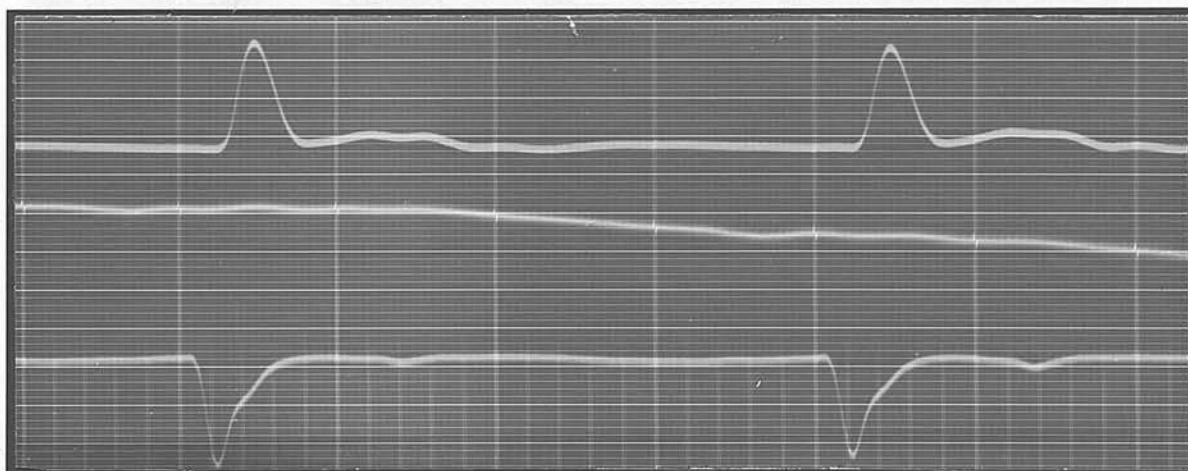


Fig. 24. BRACHIO - RADIAL (Radial artery).

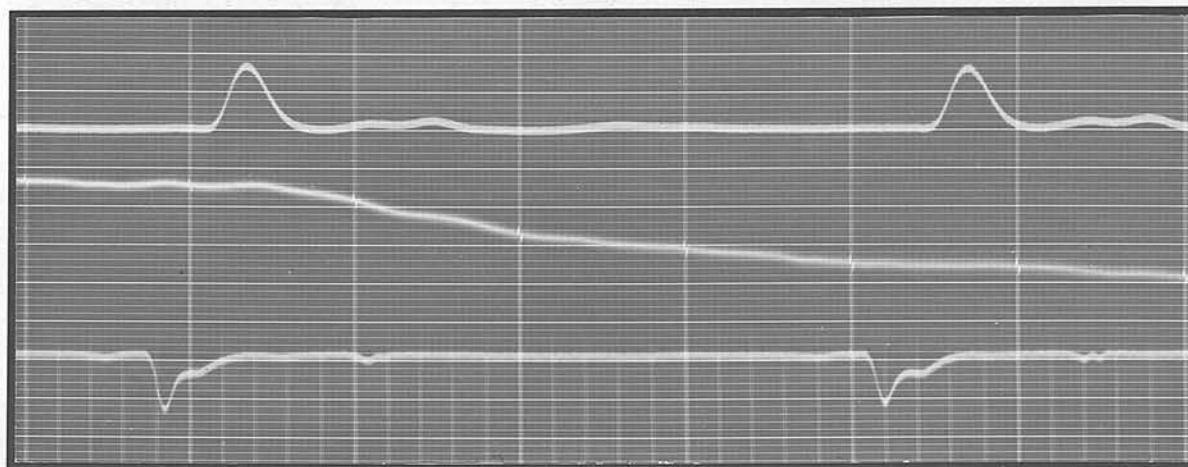


Fig. 25. CAROTID - RADIAL (Whole arm).



RECORDS FROM THE LEG USING TWO STRINGS SIMULTANEOUSLY.

Time intervals 0.2 of a second.

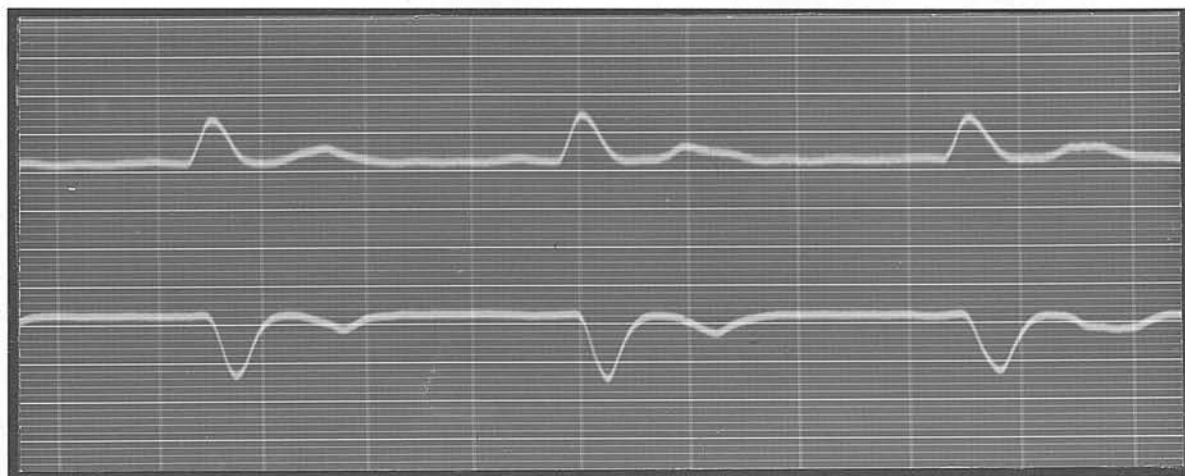


Fig. 26. FEMORAL - POPLITEAL (Femoral artery).

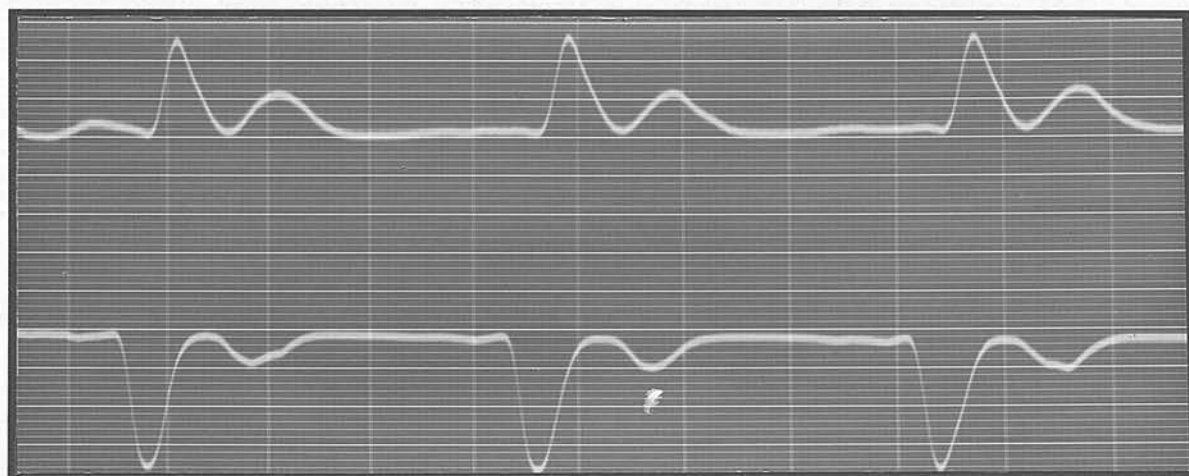


Fig. 27. POPLITEAL - ANT. TIBIAL (Ant. Tibial artery).

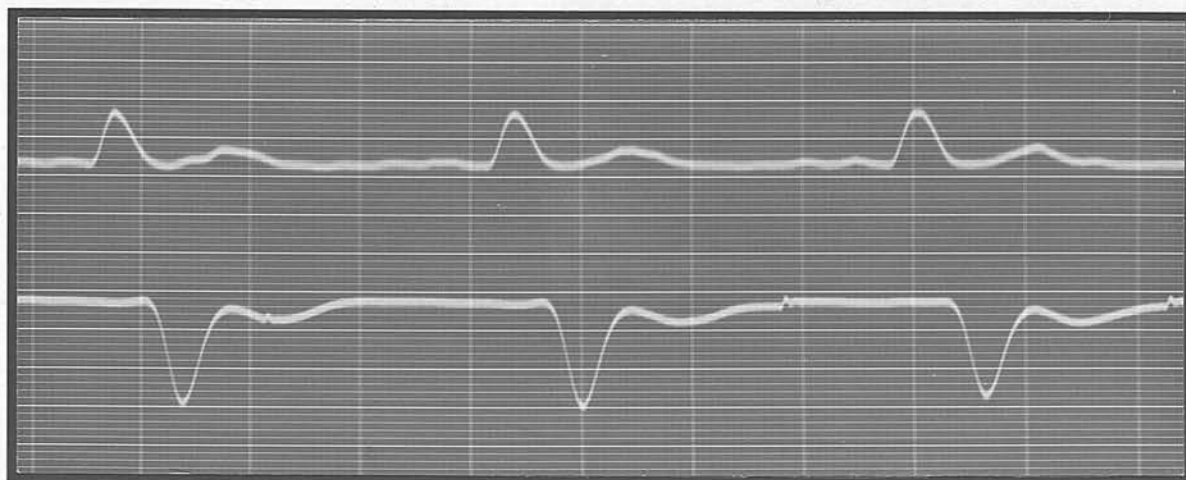


Fig. 28. FEMORAL - ANT. TIBIAL (Whole leg).

RECORDS FROM THE ARM USING THREE STRINGS SIMULTANEOUSLY.

Time intervals 0.04 of a second.

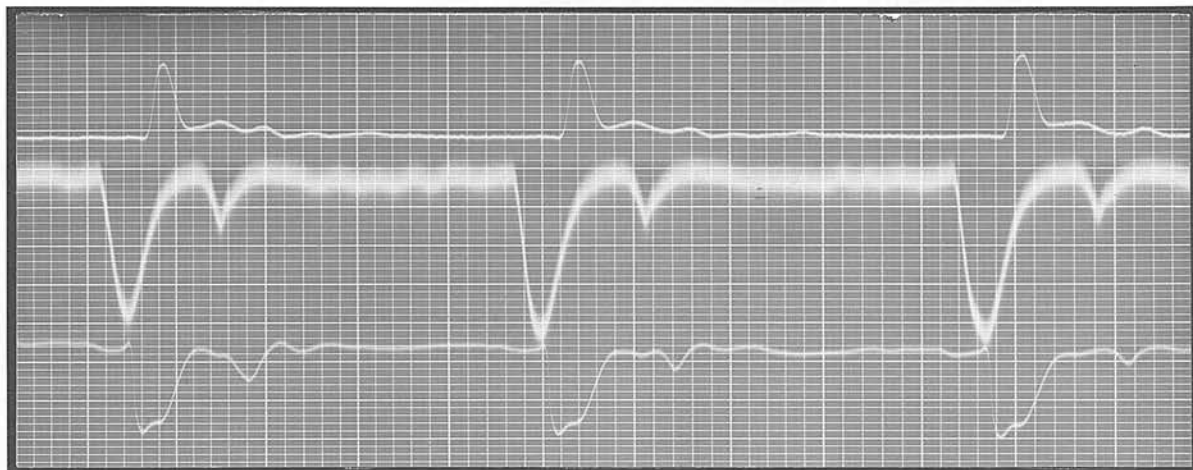


Fig. 29. CAROTID - BRACHIAL - RADIAL.  
(Without respiratory tracing).

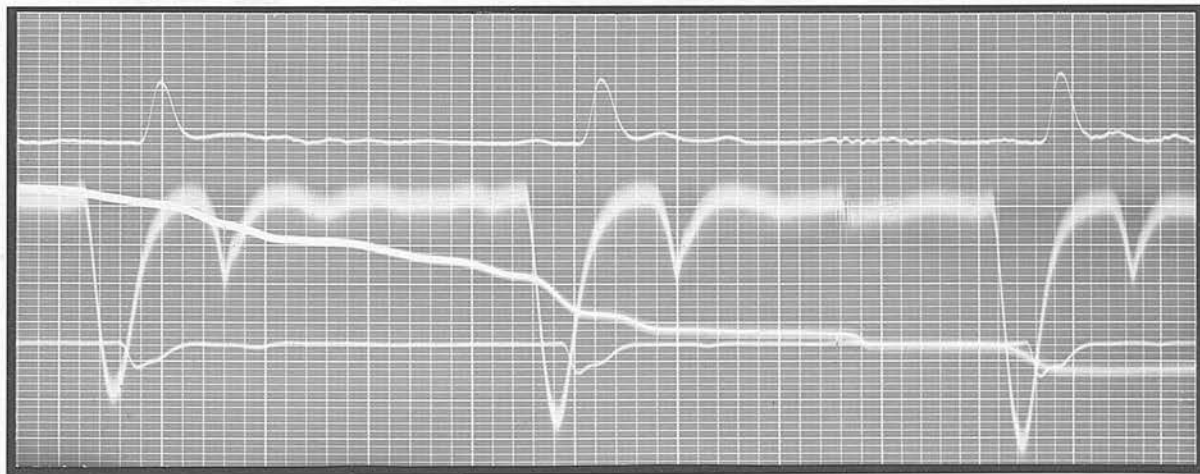


Fig. 30. CAROTID - BRACHIAL - RADIAL.  
RESPIRATORY RECORD - Inspiration up.

Upper tracing.....Radial artery  
Middle tracing.....Carotid artery  
Lower tracing.....Brachial artery

### Selection of Records.

In each experiment the record taken included about fifteen cycles, and from these a selection was made by the eye of a consecutive group of three or four, in which the deflections appeared to be well marked. These were measured up and the average taken. As will be seen later, respiratory variations in the time intervals do not as a rule exceed 12 per cent. No records therefore were accepted in which readings varied by more than 15 per cent. Consecutive cycles were measured with the object of eliminating the effect which respiration has on the pulse wave velocity. In the ordinary course of events, some four beats of the pulse occur during each respiratory cycle: thus, by taking four consecutive cycles, an average is obtained which covers both inspiratory and expiratory periods. As the effect of respiration on the pulse-wave velocity varied considerably in different individuals, this appeared a more accurate method than that of taking a respiratory curve and measuring only the cycles which coincided with inspiration or, alternatively, with expiration.



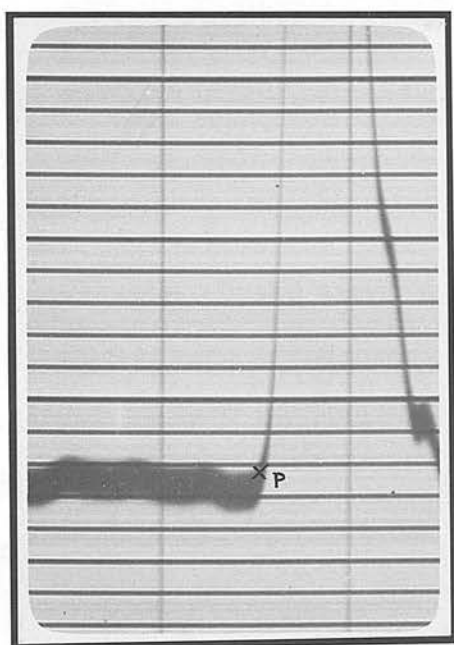
MEASUREMENT POINT.

Fig. 31.

Enlargement (x6) of hot-wire record. The point of intersection of the cross lines at P is taken for purposes of measurement as the commencement of the pulse wave. The two time lines are separated by an interval of 0.1 of a second.

### Measurement Point.

In order to obtain consistency, a constant point was selected on the records for measurement purposes. In all cases the reading was taken at the mid point of the upstroke where it was intersected by an imaginary prolongation of the upper edge of the base line. This point is shown in Fig. 31 by the intersecting lines at the letter P.

Although the selection of this point as representing the commencement of the upstroke of the wave is somewhat arbitrary, it was necessary to adopt some convention as to the point from which to measure. This convention was used throughout, and thus the results are all comparable with one another.

It may be mentioned at this point that all observations on the velocity of the pulse wave referred to in this investigation have been made at the diastolic pressure on account of the fact that the front of the pulse wave has been employed for measurement purposes.

### THE ACCURACY OBTAINABLE

The possible sources of error associated with the method may be discussed under three headings:-

- (1) The instruments.
- (2) The measurement of the artery.
- (3) The measurement of the record.

#### (1) The Instruments:

With the hot-wire method, the deflections produced in the galvanometer are so large that the strings used can be very tight, and a string with a complete natural period of 0.003 of a second is more than sufficiently sensitive. By employing a dial shunt in the galvanometer circuit, it is possible to vary the amount of current passing through the string, and in this way the natural vibrations of the string may be damped. The smaller the resistance, the greater is the damping effect, and it is found that with a resistance of about 30 Ohms between the galvanometer terminals, the natural vibrations of the string are critically damped. In this condition the galvanometer is

capable of following very rapid changes without contamination with its own vibrations, and any oscillations which appear on the record must, therefore, be due to some external cause and not to the mechanical properties of the recording instrument.

The hot wires and their containers, being of uniform construction, responded equally to cooling by the pulse waves and, as great care was taken to ensure uniformity of structure and length of the connecting tubes, the distance between the receiver and the hot wire was in all cases the same.

A length of pipe 'd' closed at one end resonates with a frequency of  $a/4d$ , where 'a' is the velocity of sound. In the narrow connecting tubes used, which have a bore of 4 mm., the velocity of sound is about 280 metres per second. Thus, in using tubes 18 inches long or rather less than one half of a metre, we may expect vibrations of the air with a frequency of not less than 140 per second, which is considerably in excess of any oscillations likely to occur in an artery.

(2) Measurement of the Artery:

While great care was exercised in the measurement of the length of the artery, no allowance could be made for the possible tortuosity of the vessel. It is reasonable to assume, however, that in measuring the arterial trunk in the arm, the average length of which was about 50 cms., the total error would not be greater than 2 cms.

In estimating the lengths of the brachial and radial arteries, a more accurate measurement of the length is possible, but as the section of artery under consideration is shorter, the net effect of the errors in both cases is approximately the same.

(3) Measurement of the Record:

By frequent calibration of the time marker, any error due to timing was eliminated, and the error in the estimation of the time interval between two impulses was therefore limited to the actual measurement of the record. With suitable tracings, giving sharp deflections, the limits of error, using the Elliot measuring machine, were  $\pm 0.001$  of a second.

It will be seen then that the error in the estimation of the pulse wave velocity may, for practical purposes, be resolved into two factors, namely the measurement of the length of the artery and the determination of the time interval. The average length of the combined brachial and radial arteries was approximately 50 cms., and the average time interval for this system was 0.08 of a second.

In a relation of the form,  $V = \frac{L}{T}$ , such as we have here, where  $V$  = velocity,  $L$  = the length of artery, and  $T$  = the time interval, it can be shown mathematically that the fractional error in  $V$  is equal to the sum of the fractional errors in  $L$  and  $T$ .

The fractional error may thus be expressed as equal to:-

$$\frac{2}{50} + \frac{0.001}{0.080} = 5\% \text{ approximately.}$$

#### Velocity of blood flow:

The velocity of the pulse wave depends on two factors chiefly:

- (1) The velocity of the blood in the artery.
- (2) The extensibility of the arterial wall.



Any experimental estimation of the pulse wave velocity will thus represent the velocity of the wave relative to the blood, plus the velocity of the blood in the artery.

The velocity of the blood varies at different periods of the cardiac cycle, being greatest during systole. It is also affected by local or general conditions, and would thus produce a corresponding alteration in the velocity of the pulse wave.

According to Clark (24) the average velocity of the blood in the aorta of man is about 0.7 metres per second. Luciani (84) gives the following figures for blood velocity:-

In the aorta - 0.75 metres per second,

In the carotid - 0.25 metres per second.

In the capillaries the velocity of the blood flow is less than 1 mm. per second.

There is therefore a progressive diminution in the rate of blood flow which will introduce a small error in the estimations.

If we assume the diminution in the velocity of the blood flow to be uniform, the probable mean

rate of blood flow may be estimated mathematically. In the brachial artery this works out at about 0.08 metres per second, while in the radial artery the calculated mean rate of blood flow is 0.01 metres per second.

It will be seen then that the error due to this factor is very small in the case of the brachial artery and practically negligible in the case of the radial artery.



VOLUME ONE

— oOo —

SECTION

THREE

— oOo —

## EXPERIMENTAL RESULTS

### THE EVOLUTION OF THE TECHNIQUE:

Various receivers.

Records from the brachial artery.

Effect of pressure in receivers.

Accuracy tested by using two strings only.

### PULSE WAVE VELOCITY IN THE ARM:

Respiratory variation.

Age and pulse wave velocity.

Blood pressure and pulse wave velocity.

### PULSE WAVE VELOCITY IN THE LEG:

Results given by normal subjects.

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## EXPERIMENTAL RESULTS

With the object of ensuring the greatest accuracy, experiments were conducted to elucidate errors in the technique. Previous observers (14)(16)(17) (60), using the hot wire method, employed a sphygmomanometer bandage as a receiver for the radial artery, but this method was discarded, as it did not seem possible to determine the point at which the impulse was transmitted to the bandage, since the extent to which the bandage was in contact with the artery would vary with the pressure in the bandage. Furthermore, varying pressures in the bandage alter the conditions of pressure in the artery, both directly and by obstructing the venous return.

To obviate pressure effects and to obtain an accurate point on the artery for measurement purposes, investigations were made with a radial pulse recorder as made by Jacquet. In a number of investigations, in estimating the carotid radial

pulse wave interval, a comparison of the results obtained in the same individual showed that where-as the use of a sphygmomanometer bandage gave inconsistent results, those obtained with the Jacquet receiver under the same conditions agreed to within  $\pm 0.001$  of a second when impulses occurring in the same phase of respiration were compared.

Attention was then directed to the methods of obtaining records from the brachial artery. It is possible to record pulsations of the brachial artery by a tambour as used for the radial artery, but the records are difficult to obtain and this method cannot easily be used as a routine; a hollow rubber bandage was therefore employed. Bramwell, McDowall and McSwiney (17) in 1923 demonstrated that the pulse-wave velocity in the section of the artery under a sphygmomanometer bandage may alter even with small applied pressures. Accordingly, a narrow bandage with an effective breadth of 2 cms. was procured, thus limiting the error in measurement of the artery at this point to  $\pm 1$  cm. and reducing to a minimum the length of artery subject to pressure changes. The effect of different

pressures in this narrow bandage was then investigated, and estimations of the pulse-wave velocity were made in the brachial and radial arteries with increasing pressures in the radial armlet. The results which were obtained from three normal individuals are set forth in Table 1 and illustrate the effect of the factor of pressure in the receiver.

It will be seen that with a pressure in the bandage at the elbow less than the diastolic pressure of the subject, little effect was produced and that with pressures of 40 mm. Hg., or less, practically no effect was apparent. As soon as the applied pressure exceeded the diastolic pressure, however, there was a definite increase in the pulse wave velocity above the bandage and a corresponding decrease below.

TABLE 1.EFFECT OF PRESSURE IN RECEIVER AT ELBOWEXPERIMENT 1.

Subject age 20.

B.P. 128/76.

| Applied pressure in receiver mm.Hg. | Mean pulse-wave velocity in metres per second |               |           |
|-------------------------------------|---|---------------|-----------|
|                                     | Brachial artery                               | Radial artery | Whole arm |
| 20                                  | 4.6   | 10.4          | 6.4       |
| 40                                  | 4.6   | 11.5          | 6.6       |
| 60                                  | 5.0   | 10.6          | 6.8       |
| 80                                  | 5.4   | 9.4           | 6.9       |
| 100                                 | 5.7   | 8.0           | 6.9       |
| 120                                 | 5.8   | 6.9           | 6.2       |

EXPERIMENT 2.

Subject age 26.

B.P. 120/68.

| Applied pressure in receiver mm.Hg. | Mean pulse-wave velocity in metres per second |               |           |
|-------------------------------------|---|---------------|-----------|
|                                     | Brachial artery                               | Radial artery | Whole arm |
| 20                                  | 4.0   | 9.0           | 5.5       |
| 40                                  | 4.0   | 8.4           | 5.5       |
| 60                                  | 4.1   | 8.3           | 5.6       |
| 80                                  | 4.6   | 6.5           | 5.4       |
| 100                                 | 4.7   | 6.1           | 5.3       |
| 120                                 | 4.9   | 5.5           | 5.2       |

EXPERIMENT 3.

Subject age 34.

B.P. 122/86.

| Applied pressure in receiver mm.Hg. | Mean pulse-wave velocity in metres per second |               |           |
|-------------------------------------|---|---------------|-----------|
|                                     | Brachial artery                               | Radial artery | Whole arm |
| 20                                  | 5.1   | 11.5          | 7.4       |
| 40                                  | 5.1   | 11.3          | 7.8       |
| 60                                  | 5.2   | 11.1          | 7.8       |
| 80                                  | 5.8   | 10.4          | 7.4       |
| 100                                 | 5.9   | 9.4           | 7.5       |
| 120                                 | 6.0   | 8.9           | 7.4       |

In order to test further the accuracy of the method which it was intended to use in the routine investigation, namely a Jacquet receiver at the wrist for recording the pulsations of the radial artery, and a narrow hollow rubber bandage applied to the brachial artery, records were taken of the pulse-wave velocity in each system. Using a double fibre case in the galvanometer, a record of the pulse-wave velocity between the carotid and brachial receivers was first made, followed by a record between the brachial and radial receivers. The narrow bandage at the elbow was then removed, and the pulse-wave velocity between the carotid and radial receivers was recorded. With the pressures in the narrow bandage as low as possible and in no experiment exceeding 40 mm. Hg., the time interval of the pulse wave between carotid and radial receivers was found to approximate extremely closely to the sum of the time intervals of the pulse wave in the brachial and radial arteries.

A protocol of a typical experiment is portrayed in Table 2, and the results of a number of experiments are summarised in Table 3. From these results it will be seen that the method suggested does not effect any appreciable error in the records.



TABLE 2.

|                       |  |
|-----------------------|--|
| Name                  | J.P.H.                                       |
| Age                   | 21.  |
| Measurements:-        |  |
|                       | Sterno clavicular joint to Carotid 9.0 cm.   |
|                       | Sterno clavicular joint to Brachial 38.0 cm. |
|                       | Sterno clavicular joint to Radial 62.5 cm.   |
| Apparatus:-           |  |
|                       | Carotid.....2 cm. glass funnel.              |
|                       | Brachial.....Narrow rubber bandage 40.mm.Hg. |
|                       | Radial.....Jacquet receiver.                 |
| CAROTID-BRACHIAL:-    |  |
| (Brachial artery)     | 0.0624                                       |
| (29.0 cm.)            | 0.0644                                       |
|                       | 0.0632                                       |
|                       | 0.0600                                       |
| Average               | 0.0625                                       |
|                       | 4.64 metres per second.                      |
| BRACHIO-RADIAL:-      |  |
| (Radial artery)       | 0.0332                                       |
| (24.5 cm)             | 0.0340                                       |
|                       | 0.0348                                       |
|                       | 0.0344                                       |
| Average               | 0.0341                                       |
|                       | 7.18 metres per second.                      |
| CAROTID-RADIAL:-      |  |
| (Whole arm)           | 0.0964                                       |
| (53.5 cm)             | 0.0960                                       |
|                       | 0.0952                                       |
|                       | 0.0948                                       |
| Average               | 0.0956                                       |
|                       | 5.59 metres per second.                      |
| <u>SUMMARY:-</u>      |  |
|                       | Time interval                                |
|                       | Pulse-wave velocity                          |
| Brachial artery       | 0.0625 )                                     |
| Radial artery         | 0.0341 )... 0.0966                           |
|                       | 5.54   |
| Whole arm .....       | 0.0956                                       |
|                       | 5.59   |
| Difference .....      | 0.0010                                       |
|                       | 0.05   |
| Approximate error.... | 1%.  |



TABLE 3.RESULTS OF EXPERIMENTS TO ELUCIDATE POSSIBLE ERROR

due to

RECEIVER AT ELBOW.

| No. | Age | Mean time interval in seconds |                       |        |                   | Difference<br>(A+B) -C |
|-----|-----|-------------------------------|-----------------------|--------|-------------------|------------------------|
|     |     | A<br>Brachial<br>artery       | B<br>Radial<br>artery | A+B    | C<br>Whole<br>arm |                        |
| 1   | 21  | 0.0625                        | 0.0341                | 0.0966 | 0.0956            | 0.0010                 |
| 2   | 21  | 0.0619                        | 0.0475                | 0.1094 | 0.1091            | 0.0003                 |
| 3   | 22  | 0.0562                        | 0.0546                | 0.1108 | 0.1100            | 0.0008                 |
| 4   | 24  | 0.0542                        | 0.0301                | 0.0843 | 0.0820            | 0.0023                 |
| 5   | 25  | 0.0544                        | 0.0347                | 0.0891 | 0.0885            | 0.0006                 |
| 6   | 26  | 0.0610                        | 0.0365                | 0.0975 | 0.0947            | 0.0028                 |
| 7   | 27  | 0.0477                        | 0.0455                | 0.0932 | 0.0908            | 0.0024                 |
| 8   | 31  | 0.0495                        | 0.0345                | 0.0840 | 0.0817            | 0.0023                 |
| 9   | 31  | 0.0507                        | 0.0431                | 0.0938 | 0.0908            | 0.0030                 |
| 10  | 34  | 0.0505                        | 0.0304                | 0.0809 | 0.0804            | 0.0005                 |
| 11  | 52  | 0.0515                        | 0.0295                | 0.0810 | 0.0797            | 0.0013                 |
| 12  | 55  | 0.0477                        | 0.0293                | 0.0770 | 0.0752            | 0.0018                 |

Average Carotid-radial time interval...0.0889

Average "Difference".....0.0016

Mean error.....1.8%

TABLE 4.

RESULTS OF EXPERIMENTS TO TEST ACCURACY OF METHOD  
in  
LOWER LIMB.

| No. | Age | Mean time interval in seconds |                           |        |                   | Difference<br>(A+B) - C |
|-----|-----|-------------------------------|---------------------------|--------|-------------------|-------------------------|
|     |     | A<br>Femoral<br>artery        | B<br>Ant.Tibial<br>artery | A + B  | C<br>Whole<br>Leg |                         |
| 1   | 20  | 0.0292                        | 0.0581                    | 0.0873 | 0.0845            | 0.0028                  |
| 2   | 20  | 0.0253                        | 0.0595                    | 0.0848 | 0.0852            | 0.0004                  |
| 3   | 20  | 0.0296                        | 0.0529                    | 0.0825 | 0.0812            | 0.0013                  |
| 4   | 21  | 0.0327                        | 0.0529                    | 0.0856 | 0.0837            | 0.0019                  |
| 5   | 21  | 0.0213                        | 0.0457                    | 0.0670 | 0.0670            | -                       |
| 6   | 22  | 0.0247                        | 0.0572                    | 0.0819 | 0.0794            | 0.0025                  |
| 7   | 25  | 0.0285                        | 0.0696                    | 0.0981 | 0.1000            | 0.0019                  |
| 8   | 26  | 0.0289                        | 0.0478                    | 0.0767 | 0.0748            | 0.0019                  |
| 9   | 31  | 0.0164                        | 0.0485                    | 0.0649 | 0.0654            | 0.0005                  |
| 10  | 32  | 0.0158                        | 0.0482                    | 0.0640 | 0.0669            | 0.0029                  |
| 11  | 33  | 0.0216                        | 0.0446                    | 0.0662 | 0.0643            | 0.0021                  |
| 12  | 34  | 0.0263                        | 0.0564                    | 0.0827 | 0.0829            | 0.0002                  |

Average time interval for Whole leg...0.0779

Average "Difference".....0.0015

Mean error.....1.9%.

Similar experiments were conducted on the lower limb, and it was found that the greatest accuracy was obtained when the procedure outlined in Section II was followed, namely a tambour for recording pulsations of the femoral artery, and a pneumatic rubber ball for recording pulsations of the popliteal artery at the knee and the dorsalis pedis artery at the ankle. The results of twelve experiments are summarised in Table 4.

Having established an accurate technique, two galvanometers were then employed in series as previously described, so that three pulse waves could be simultaneously recorded, the carotid, brachial and radial in the arm, or the corresponding points in the leg.

The various physiological factors which might influence pulse-wave velocity were then considered, and the effect of these factors on the pulse-wave velocity in different arteries was investigated.

## RESPIRATION AND PULSE WAVE VELOCITY

As early as 1733, Stephen Hales (54) drew attention to the fact that there is a periodic variation in blood pressure synchronous with the respiratory phases. The exact nature of this variation and the factors which are responsible for its occurrence have been investigated from different angles by many observers, and with very varying results. Lewis (80) in 1908 drew attention to the fact that the relationship varied in different individuals and was dependent upon the type of breathing. This observer came to the conclusion that thoracic inspiration was associated with a fall in blood pressure, while diaphragmatic inspiration produced a rise in blood pressure.

Erlanger and Festerling (37) in 1912 investigated the relationship between blood pressure and respiration in man and found a fall in systolic blood pressure associated with inspiration and an immediate rise on expiration.

Gaisbock (49) in 1913 found an increase in blood pressure associated with inspiration, and



suggested that this might be due to reflex vasoconstriction. Mathieu and Merklar (90), however, in 1924 came to the conclusion that the respiratory alterations in the blood pressure were not due to a nervous factor.

About the same time, Visschner, Rupp and Scott (116) investigated the subject by animal experiment and found that inspiration produced a rise in blood pressure after a latent period of about two to four heart beats. These observers were of opinion that the rise in blood pressure was due to stretching and consequent narrowing of the vessels in the lung during inspiration; further, that with a lowering of the intra-thoracic pressure the blood could flow more easily to the atria. According to their explanation, the net effect was dependent on the pulse respiration ratio.

Barry (53) in 1926 found a rise in blood pressure associated with expiration, and attributed this to the fact that with expiration there is a greater return of blood to the heart and thus an increased output. Du Bois Raymond (30) on the other hand, about the same time, obtained a rise in blood pressure with inspiration.

The problem was reinvestigated by Heinbecker (59) in 1927, and this observer found that in man inspiration was invariably associated with a fall both in systolic and diastolic blood pressure, while with expiration there was a rise both in systolic and diastolic pressures. His findings were confirmed by animal experiment, and he showed that the rise in blood pressure associated with expiration was due to the increased outflow from the lungs, which occurred as a result of the diminution in the size of the vascular field, forcing out the blood which it contained. The subsequent fall in pressure was due to the diminished inflow caused by increased resistance when the lungs were deflated. This observer maintained that the only factors responsible for the production of respiratory waves in blood pressure were the changes in vascular capacity and resistance in the pulmonary bed, accompanying inflation and deflation of the lungs.

This view was to some extent contradicted in 1928 by Johnson and Luckhardt (72), who maintained that a fall in systolic blood pressure occurred when the intra-pulmonary pressure was raised.

Vincent and Thompson (115) also found a fall in blood pressure with deep inspiration, which they attributed to mechanical interference with the return of blood to the heart.

It would appear to be accepted by all that the venous return to the right heart is augmented during inspiration and decreased during expiration. This was shown experimentally by Haller (56) in 1879 and has since been confirmed by other observers. The factors responsible for this are the lowered intra-thoracic pressure sucking the blood into the chest, and the raised intra-abdominal pressure forcing the blood out of the abdomen. The output of the right ventricle is thus increased during inspiration and decreased during expiration. Wiggers (123) determined the pressure changes in the pulmonary artery, and found that during inspiration there was a fall both in systolic and diastolic blood pressure in the pulmonary artery, while during expiration a rise in both pressures was observed. This observation is in agreement with Heinbecker's view that there is a diminished resistance to the blood flow during the inspiratory

phase of respiration. Furthermore, it seems rational to assume that it would be most advantageous to the organism to have the pulmonary vascular capacity greatest during inspiration, when a fresh supply of air is available for oxygenation of the blood.

The relationship between respiration and blood pressure has been recorded graphically in a number of individuals, and in each case it was found that the expiratory phase was associated not only with a rise in systolic and diastolic pressure, but also with an increase in pulse pressure.

The method adopted was as follows. A sphygmomanometer bandage was fixed round the arm above the elbow and connected to a T tube, one limb of which communicated with a pressure manometer and the other with a Mary's sphygmoscope. From this a tube led to a tambour recording on a revolving drum with smoked paper. The sphygmomanometer bandage was inflated to a pressure slightly in excess of the diastolic pressure of the subject; thus the tracing obtained indicated changes both of the systolic and diastolic pressures. A simultaneous record of



respiration was taken by the method described in Section II (p. 33), the movements of the arm of the tambour being recorded on the smoked paper instead of photographically.

The arrangement of the sphygmoscope is shown in Fig. 32, and two tracings obtained by this method are reproduced in Figs. 33 and 34.

GENERAL ARRANGEMENT OF APPARATUS FOR SIMULTANEOUS  
RESPIRATORY AND BLOOD-PRESSURE RECORDS

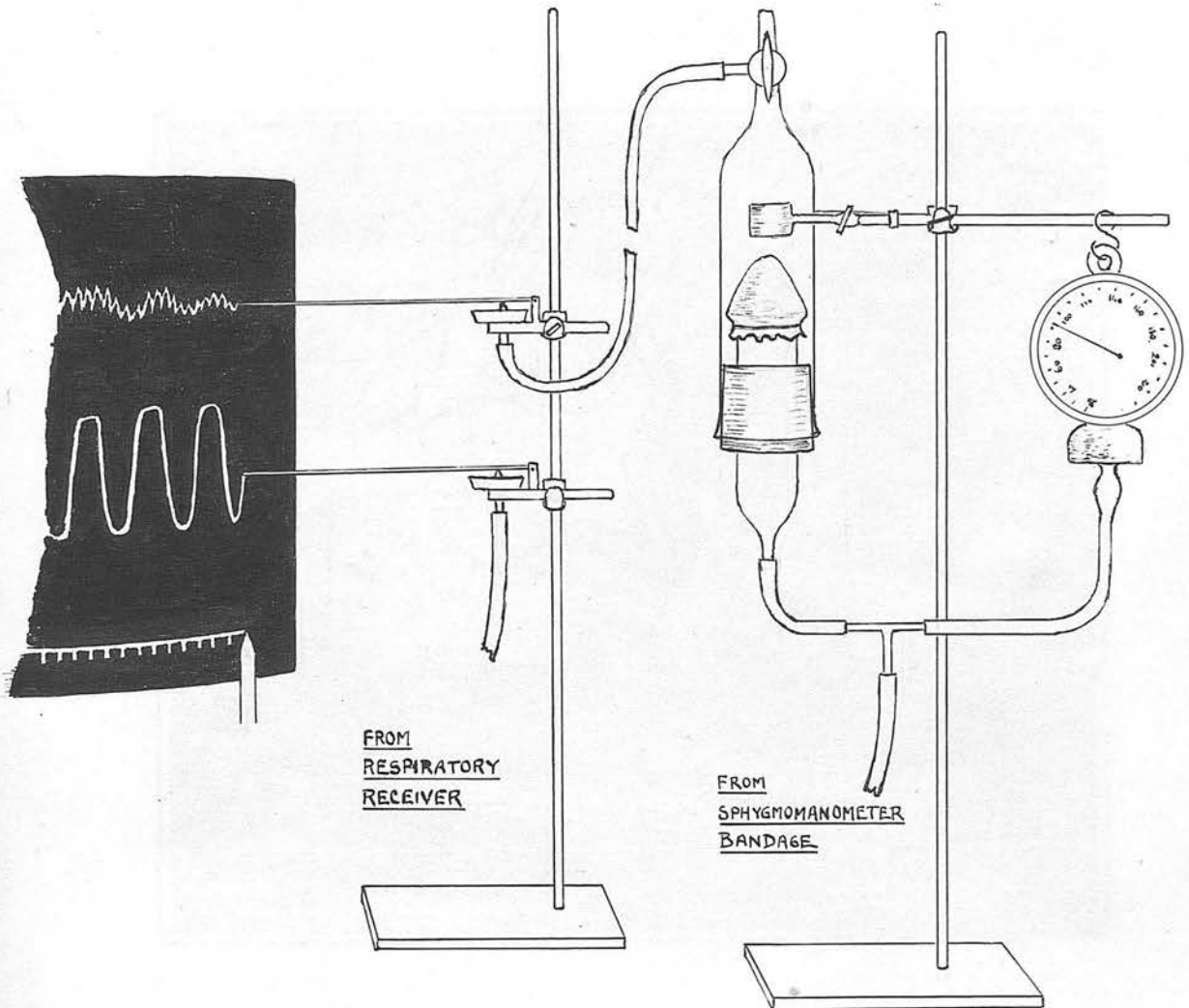
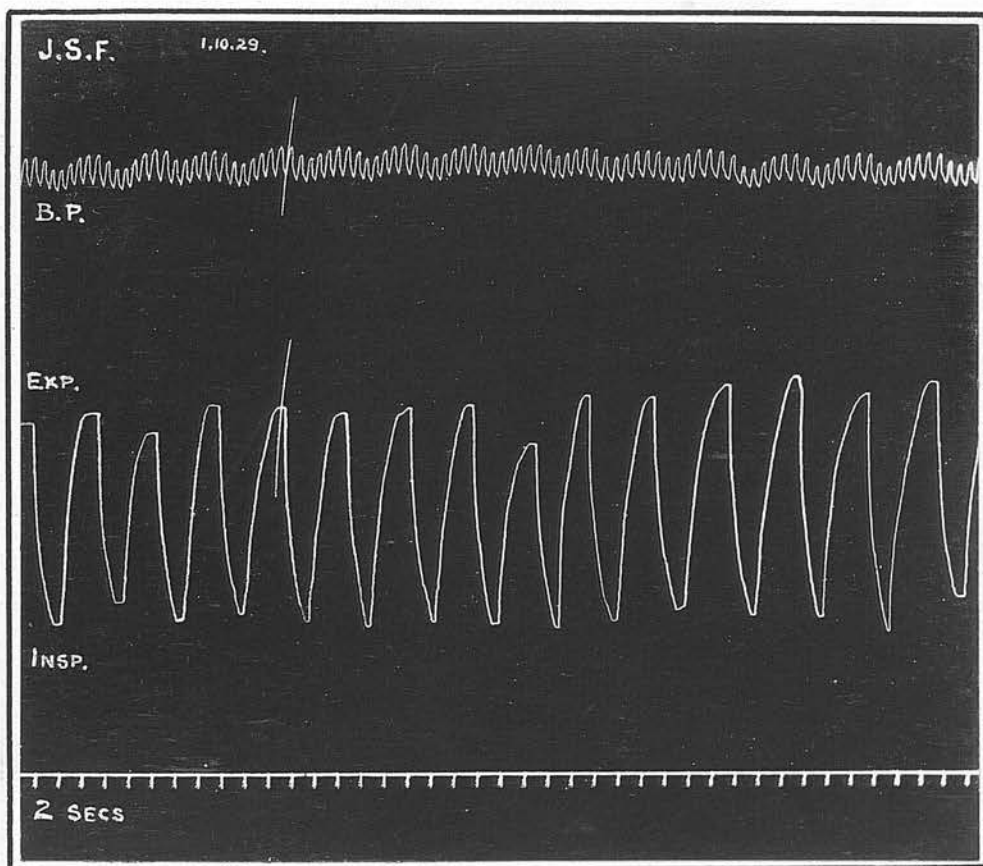


FIG. 32.

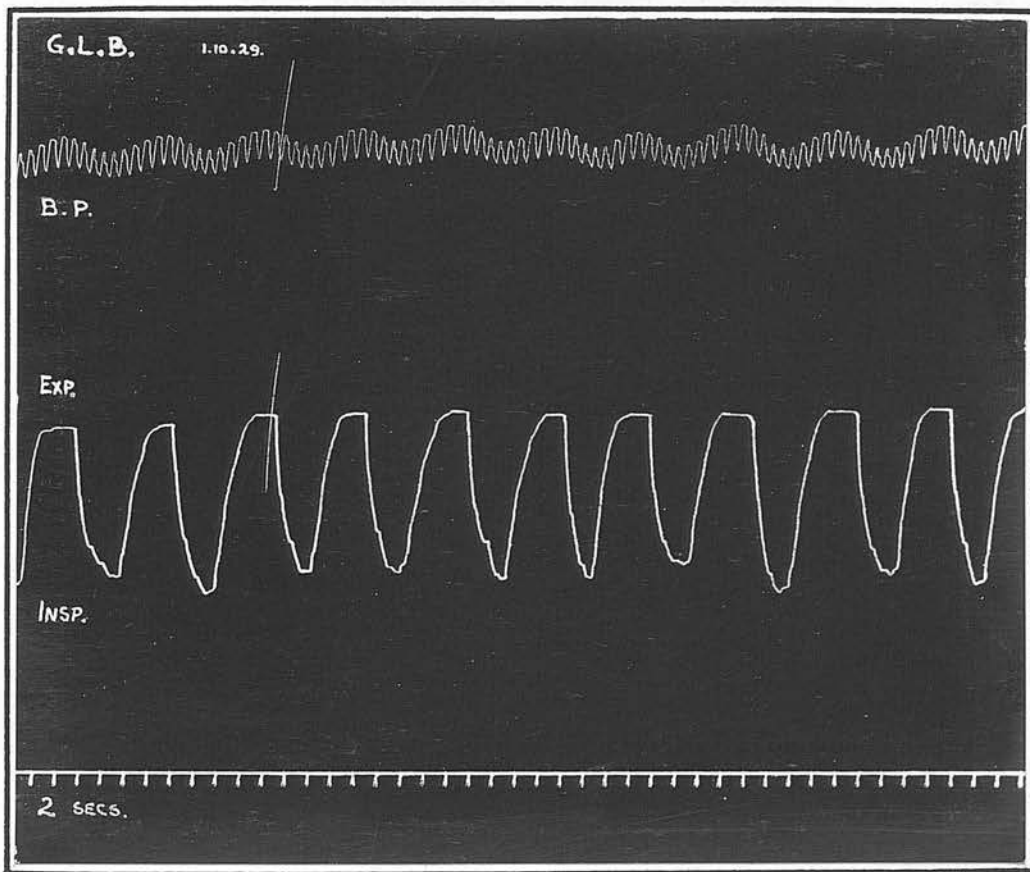
RESPIRATORY VARIATION

in

BLOOD PRESSUREFig. 33.

RESPIRATORY VARIATION

in

BLOOD PRESSUREFig. 34.

As is to be expected, the respiratory variation in blood pressure is associated with a variation in the pulse-wave velocity in the arterial system, and Hickson and McSwiney (62) in 1924 drew attention to the effect which this factor had on the time intervals between carotid and radial pulses.

The respiratory variation in the pulse-wave velocity in the brachial and radial arteries has been investigated, and the results of twelve experiments are given in Table 5. These results are portrayed graphically in Fig. 35.

It will be seen that in all cases there is an alteration in pulse-wave velocity associated with respiration. This variation is more marked in some cases than others, but in all cases the pulse-wave velocity is higher during the expiratory phase of respiration. This is in accordance with previous observations and is attributable to the rise in blood pressure associated with expiration.

TABLE 5.RESPIRATORY VARIATION

in

PULSE-WAVE VELOCITY

| No. | Age | Mean pulse-wave velocity in metres per second |      |       |               |      |       |           |      |       |
|-----|-----|---|------|-------|---------------|------|-------|-----------|------|-------|
|     |     | Brachial artery                               |      |       | Radial artery |      |       | Whole arm |      |       |
|     |     | Insp.   | Exp. | Diff. | Insp.         | Exp. | Diff. | Insp.     | Exp. | Diff. |
| 1   | 14  | 4.5   | 4.7  | 0.2   | 4.2           | 5.3  | 1.1   | 4.3       | 4.9  | 0.6   |
| 2   | 15  | 4.4   | 4.6  | 0.2   | 8.6           | 8.8  | 0.2   | 5.9       | 6.1  | 0.2   |
| 3   | 17  | 4.3   | 4.6  | 0.3   | 9.6           | 10.1 | 0.5   | 6.0       | 6.4  | 0.4   |
| 4   | 19  | 5.6   | 5.8  | 0.2   | 8.9           | 9.1  | 0.2   | 6.8       | 7.0  | 0.2   |
| 5   | 20  | 4.0   | 4.1  | 0.1   | 8.7           | 8.9  | 0.2   | 5.6       | 5.7  | 0.1   |
| 6   | 24  | 4.6   | 4.6  | -     | 7.0           | 7.1  | 0.1   | 5.0       | 5.0  | -     |
| 7   | 26  | 3.9   | 4.1  | 0.2   | 8.6           | 9.3  | 0.7   | 5.3       | 5.8  | 0.5   |
| 8   | 32  | 5.6   | 6.0  | 0.4   | 8.5           | 9.5  | 1.0   | 6.8       | 7.3  | 0.5   |
| 9   | 33  | 5.4   | 5.8  | 0.4   | 8.1           | 9.2  | 1.1   | 6.7       | 7.3  | 0.6   |
| 10  | 57  | 6.7   | 7.1  | 0.4   | 13.6          | 14.5 | 0.9   | 8.7       | 9.2  | 0.5   |



DIAGRAM SHOWING  
EFFECT OF RESPIRATION ON PULSE-WAVE VELOCITY

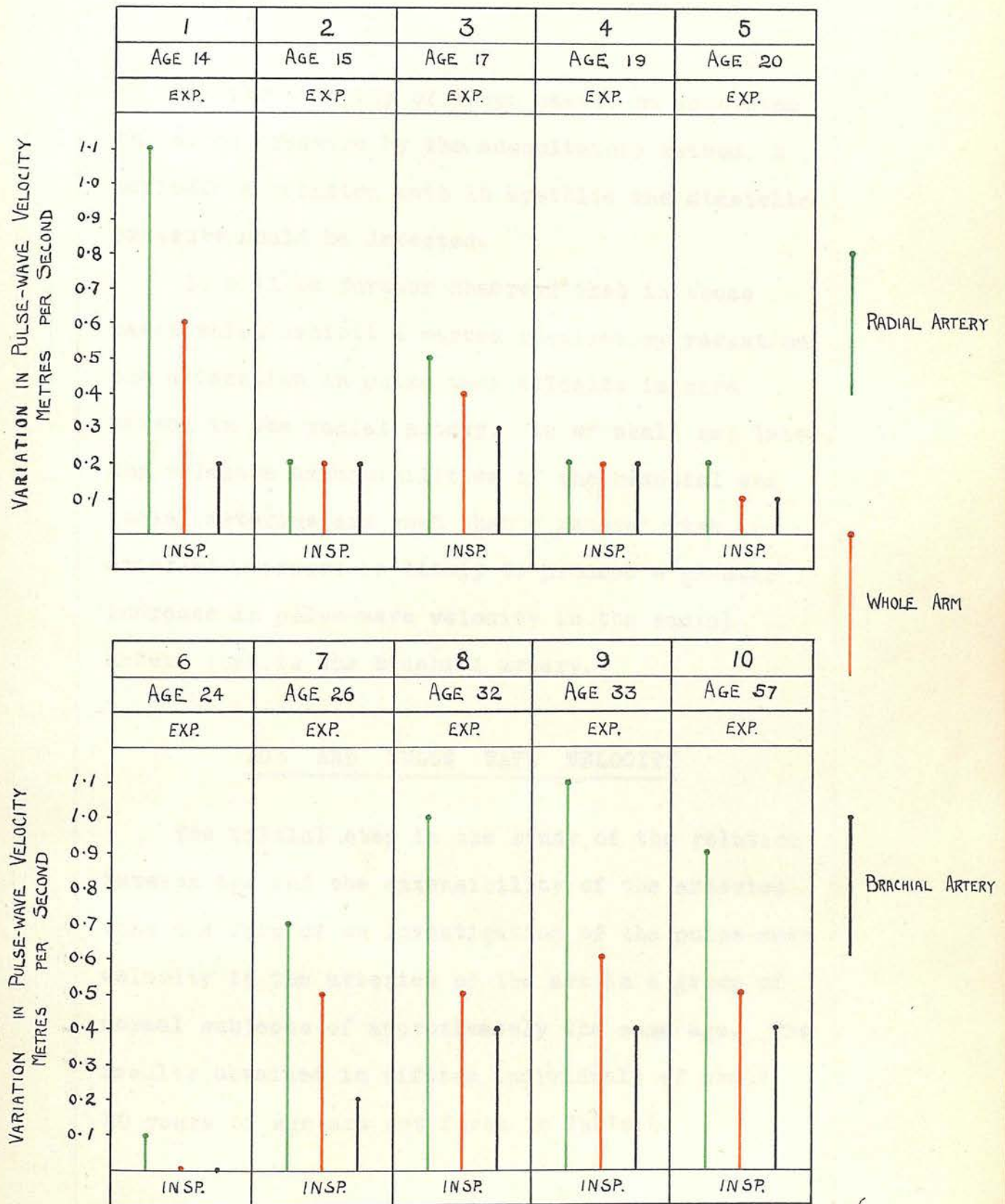


FIG. 35.

J.S.F.



In the majority of these cases, on recording the blood pressure by the auscultatory method, a periodic alteration both in systolic and diastolic pressure could be detected.

It will be further observed that in those cases which exhibit a marked respiratory variation, the alteration in pulse-wave velocity is more marked in the radial artery. As we shall see later, the relative extensibilities of the brachial and radial arteries are such that a general rise in arterial pressure is likely to produce a greater increase in pulse-wave velocity in the radial artery than in the brachial artery.

#### AGE AND PULSE WAVE VELOCITY

The initial step in the study of the relation between age and the extensibility of the arteries took the form of an investigation of the pulse-wave velocity in the arteries of the arm in a group of normal subjects of approximately the same age. The results obtained in fifteen individuals of about 20 years of age are set forth in Table 6.

TABLE 6.SUBJECTS AGED APPROXIMATELY 20 YEARS.

| No. | Age | Mean pulse-wave velocity<br>in metres per second |                  |              | Blood<br>pressure |
|-----|-----|--|------------------|--------------|-------------------|
|     |     | Brachial<br>artery                               | Radial<br>artery | Whole<br>arm |                   |
| 1   | 19  | 4.6  | 9.6              | 6.3          | 88/54             |
| 2   | 20  | 4.7  | 6.1              | 5.4          | 110/70            |
| 3   | 20  | 4.2  | 8.1              | 5.9          | 106/68            |
| 4   | 20  | 5.2  | 8.2              | 6.4          | 112/82            |
| 5   | 20  | 5.0  | 11.3             | 6.7          | 102/74            |
| 6   | 20  | 5.3  | 9.1              | 6.6          | 100/72            |
| 7   | 20  | 4.9  | 7.6              | 6.0          | 98/70             |
| 8   | 20  | 4.3  | 7.3              | 5.7          | 98/68             |
| 9   | 20  | 4.1  | 8.7              | 5.6          | 112/68            |
| 10  | 20  | 4.8  | 7.2              | 5.8          | 120/88            |
| 11  | 21  | 4.5  | 11.0             | 7.2          | 118/80            |
| 12  | 21  | 4.8  | 10.4             | 6.4          | 108/76            |
| 13  | 21  | 4.6  | 7.2              | 5.6          | 108/76            |
| 14  | 21  | 4.7  | 6.7              | 5.7          | 132/89            |
| 15  | 21  | 5.1  | 12.7             | 7.0          | 134/74            |

SUMMARY

|                  |     |      |     |
|------------------|-----|------|-----|
| Minimum          | 4.1 | 6.1  | 5.4 |
| Maximum          | 5.3 | 12.7 | 7.2 |
| <u>Variation</u> | 0.6 | 3.3  | 0.9 |

An examination of these results reveals three outstanding features:

- (1) The pulse-wave velocity in the brachial artery is in all cases lower than that in the radial artery.
- (2) While the results obtained from the brachial artery are fairly uniform, those obtained from the radial artery show considerable variation. The comparatively consistent results obtained when the pulse-wave velocity is estimated over the whole length of the arm are therefore due in large measure to the uniformity in the velocity with which the pulse wave is transmitted in the brachial artery.
- (3) No general relationship exists between the velocity of the pulse wave and the blood pressure, either systolic or diastolic.

Blood pressure is estimated clinically in the brachial artery, and if any general relationship existed one would expect to find some uniformity between the pulse-wave velocity in that artery and

the blood pressure. We find, however, that while subjects 1 and 14 have pulse-wave velocities in the brachial artery of 4.6 and 4.7 metres per second, their respective blood pressures are 88/54 and 132/89. Again, subjects 6 and 9 have similar blood pressures of 100/72 and 112/68, while their respective pulse-wave velocities in the brachial artery are 5.3 and 4.1 metres per second.

The investigation was extended to other age groups and the pulse-wave velocity in the arteries of the arm has been determined in 103 normal subjects of ages ranging from 5 to 80 years. The results of this investigation are set forth in Tables 7 to 13. Of these subjects, 53 were below the age of 25, and the remaining 50 covered the age groups above this. The number of older subjects examined was relatively smaller, but in spite of this there is a remarkable uniformity in the results obtained.

TABLE 7.SUBJECTS aged 5-15 Years.

| No.     | Age | Mean pulse wave-velocity<br>in metres per second |                  |              | Blood<br>pressure |
|---------|-----|--|------------------|--------------|-------------------|
|         |     | Brachial<br>artery                               | Radial<br>artery | Whole<br>arm |                   |
| 1       | 5   | 3.1  | 3.8              | 3.4          | 76/42             |
| 2       | 5   | 3.4  | 4.9              | 4.0          | 76/52             |
| 3       | 6   | 4.0  | 4.9              | 4.5          | 82/52             |
| 4       | 6   | 4.2  | 6.7              | 5.2          | 96/64             |
| 5       | 7   | 4.3  | 5.0              | 4.6          | 76/42             |
| 6       | 7   | 3.6  | 6.1              | 4.7          | 96/66             |
| 7       | 8   | 4.0  | 5.7              | 4.7          | 96/64             |
| 8       | 8   | 3.9  | 6.0              | 5.0          | 96/66             |
| 9       | 9   | 3.9  | 6.7              | 4.9          | 102/74            |
| 10      | 9   | 4.4  | 6.5              | 5.2          | 102/76            |
| 11      | 10  | 4.5  | 6.6              | 5.3          | 106/64            |
| 12      | 10  | 4.7  | 6.8              | 5.7          | 108/72            |
| 13      | 11  | 4.2  | 6.6              | 5.3          | 86/54             |
| 14      | 11  | 4.4  | 7.5              | 5.4          | 98/64             |
| 15      | 12  | 4.3  | 7.3              | 5.4          | 106/74            |
| 16      | 12  | 4.6  | 8.4              | 6.1          | 98/66             |
| 17      | 13  | 4.6  | 4.7              | 4.7          | 106/64            |
| 18      | 13  | 4.5  | 6.0              | 5.1          | 104/68            |
| 19      | 14  | 4.6  | 5.6              | 5.0          | 102/66            |
| 20      | 14  | 4.5  | 6.5              | 5.2          | 98/78             |
| Average |     | 4.2  | 6.0              | 4.9          | 95/63             |

TABLE 8.SUBJECTS aged 15-25 Years.

| No.     | Age | Mean pulse-wave velocity<br>in metres per second |                  |              | Blood<br>pressure |
|---------|-----|--|------------------|--------------|-------------------|
|         |     | Brachial<br>artery                               | Radial<br>artery | Whole<br>arm |                   |
| 1       | 15  | 4.5  | 5.9              | 5.1          | 104/68            |
| 2       | 15  | 4.4  | 8.6              | 5.9          | 92/50             |
| 3       | 16  | 4.1  | 8.6              | 5.6          | 112/74            |
| 4       | 16  | 4.5  | 10.1             | 6.2          | 96/68             |
| 5       | 17  | 4.7  | 7.0              | 6.0          | 112/66            |
| 6       | 17  | 5.1  | 7.3              | 5.9          | 118/84            |
| 7       | 18  | 4.3  | 11.0             | 6.3          | 112/78            |
| 8       | 18  | 4.9  | 8.5              | 6.2          | 96/64             |
| 9       | 19  | 5.7  | 10.6             | 7.3          | 118/80            |
| 10      | 19  | 4.6  | 9.6              | 6.3          | 88/54             |
| 11      | 19  | 5.6  | 9.0              | 6.9          | 120/78            |
| 12      | 20  | 4.1  | 8.7              | 5.6          | 112/68            |
| 13      | 20  | 4.8  | 7.2              | 5.8          | 120/88            |
| 14      | 20  | 4.7  | 6.1              | 5.4          | 110/70            |
| 15      | 20  | 4.3  | 7.3              | 5.7          | 98/68             |
| 16      | 20  | 4.2  | 8.1              | 5.9          | 106/68            |
| 17      | 20  | 4.9  | 7.6              | 6.0          | 98/70             |
| 18      | 20  | 5.2  | 8.2              | 6.4          | 112/82            |
| 19      | 20  | 5.3  | 9.1              | 6.6          | 100/72            |
| 20      | 20  | 5.0  | 11.3             | 6.7          | 102/74            |
| 21      | 21  | 5.6  | 7.8              | 7.6          | 114/82            |
| 22      | 21  | 4.5  | 11.0             | 7.2          | 118/80            |
| 23      | 21  | 4.7  | 6.7              | 5.7          | 132/89            |
| 24      | 21  | 4.6  | 7.2              | 5.6          | 108/76            |
| 25      | 21  | 5.1  | 12.7             | 7.0          | 134/74            |
| 26      | 21  | 5.5  | 5.5              | 5.5          | 110/72            |
| 27      | 21  | 4.8  | 10.4             | 6.4          | 108/76            |
| 28      | 22  | 5.5  | 5.9              | 5.8          | 120/92            |
| 29      | 22  | 4.1  | 6.0              | 5.1          | 100/75            |
| 30      | 24  | 4.6  | 7.0              | 5.0          | 106/64            |
| 31      | 24  | 4.5  | 9.0              | 6.5          | 104/60            |
| 32      | 24  | 4.4  | 5.8              | 5.1          | 114/76            |
| 33      | 24  | 4.6  | 10.2             | 6.4          | 108/80            |
| Average |     | 4.7  | 8.3              | 6.0          | 109/73            |

TABLE 9.

SUBJECTS aged 25-35 Years.

| No.     | Age | Mean pulse-wave velocity<br>in metres per second |                  |              | Blood<br>pressure |
|---------|-----|--|------------------|--------------|-------------------|
|         |     | Brachial<br>artery                               | Radial<br>artery | Whole<br>arm |                   |
| 1       | 25  | 5.6  | 9.6              | 7.4          | 114/66            |
| 2       | 25  | 5.5  | 9.5              | 7.6          | 114/58            |
| 3       | 25  | 4.0  | 9.2              | 6.2          | 115/65            |
| 4       | 25  | 4.3  | 11.9             | 6.3          | 112/64            |
| 5       | 26  | 4.7  | 7.5              | 5.8          | 126/86            |
| 6       | 26  | 4.5  | 7.6              | 5.9          | 110/75            |
| 7       | 26  | 4.0  | 9.0              | 5.5          | 110/68            |
| 8       | 26  | 4.8  | 10.1             | 6.4          | 110/74            |
| 9       | 27  | 4.3  | 8.6              | 6.3          | 108/66            |
| 10      | 27  | 5.0  | 9.6              | 6.4          | 108/70            |
| 11      | 27  | 4.5  | 9.3              | 6.5          | 118/90            |
| 12      | 31  | 5.4  | 7.5              | 6.1          | 115/70            |
| 13      | 31  | 6.3  | 9.0              | 7.2          | 108/78            |
| 14      | 31  | 5.6  | 8.2              | 6.6          | 98/74             |
| 15      | 32  | 4.6  | 8.4              | 6.1          | 116/68            |
| 16      | 32  | 4.5  | 8.2              | 6.0          | 116/68            |
| 17      | 32  | 6.1  | 9.6              | 7.4          | 106/76            |
| 18      | 33  | 5.8  | 9.0              | 7.1          | 112/70            |
| 19      | 33  | 5.4  | 8.1              | 6.7          | 120/80            |
| 20      | 34  | 4.6  | 8.2              | 6.6          | 120/78            |
| 21      | 34  | 5.0  | 8.1              | 6.4          | 118/78            |
| 22      | 34  | 5.4  | 9.9              | 6.9          | 102/82            |
| Average |     | 5.0  | 8.9              | 6.5          | 112/73            |



TABLE 10.

SUBJECTS aged 35-45 Years.

| No.     | Age | Mean pulse-wave velocity<br>in metres per second |                  |              | Blood<br>pressure |
|---------|-----|--|------------------|--------------|-------------------|
|         |     | Brachial<br>artery                               | Radial<br>artery | Whole<br>arm |                   |
| 1       | 35  | 5.0  | 11.9             | 6.4          | 112/86            |
| 2       | 35  | 6.2  | 10.5             | 7.8          | 118/82            |
| 3       | 35  | 4.9  | 8.9              | 6.0          | 92/58             |
| 4       | 36  | 5.9  | 13.6             | 8.1          | 118/84            |
| 5       | 36  | 5.0  | 11.4             | 7.1          | 130/84            |
| 6       | 37  | 4.8  | 13.8             | 7.1          | 108/78            |
| 7       | 40  | 5.6  | 10.4             | 7.3          | 92/62             |
| 8       | 43  | 6.6  | 9.1              | 7.7          | 124/84            |
| 9       | 43  | 5.6  | 8.2              | 6.6          | 128/82            |
| 10      | 44  | 5.6  | 6.2              | 5.9          | 110/72            |
| Average |     | 5.5  | 10.4             | 7.0          | 113/77            |

TABLE 11.

SUBJECTS aged 45-55 Years.

| No.     | Age | Mean pulse-wave velocity<br>in metres per second |                  |              | Blood<br>pressure |
|---------|-----|--|------------------|--------------|-------------------|
|         |     | Brachial<br>artery                               | Radial<br>artery | Whole<br>arm |                   |
| 1       | 47  | 4.8  | 8.0              | 6.1          | 118/76            |
| 2       | 47  | 5.8  | 13.9             | 8.2          | 126/86            |
| 3       | 47  | 5.6  | 9.8              | 7.0          | 122/94            |
| 4       | 49  | 6.2  | 13.5             | 8.4          | 174/104           |
| 5       | 50  | 5.4  | 9.0              | 6.7          | 100/64            |
| 6       | 51  | 5.3  | 10.7             | 5.9          | 124/78            |
| 7       | 52  | 4.9  | 14.7             | 6.9          | 120/82            |
| 8       | 52  | 6.4  | 14.1             | 8.7          | 122/82            |
| 9       | 52  | 5.2  | 10.7             | 6.0          | 122/78            |
| 10      | 54  | 6.5  | 9.9              | 7.7          | 112/76            |
| Average |     | 5.6  | 11.4             | 7.2          | 124/82            |

TABLE 12.SUBJECTS aged 55-65 Years.

| No.     | Age | Mean pulse-wave velocity<br>in metres per second |                  |              | Blood<br>pressure |
|---------|-----|--|------------------|--------------|-------------------|
|         |     | Brachial<br>artery                               | Radial<br>artery | Whole<br>arm |                   |
| 1       | 55  | 5.4  | 9.2              | 7.0          | 130/82            |
| 2       | 57  | 6.4  | 14.5             | 8.6          | 132/86            |
| 3       | 58  | 5.4  | 13.1             | 7.9          | 120/78            |
| 4       | 61  | 5.0  | 7.4              | 5.9          | 158/62            |
| 5       | 65  | 6.0  | 11.0             | 7.4          | 112/70            |
| Average |     | 5.6  | 11.0             | 7.4          | 130/75            |

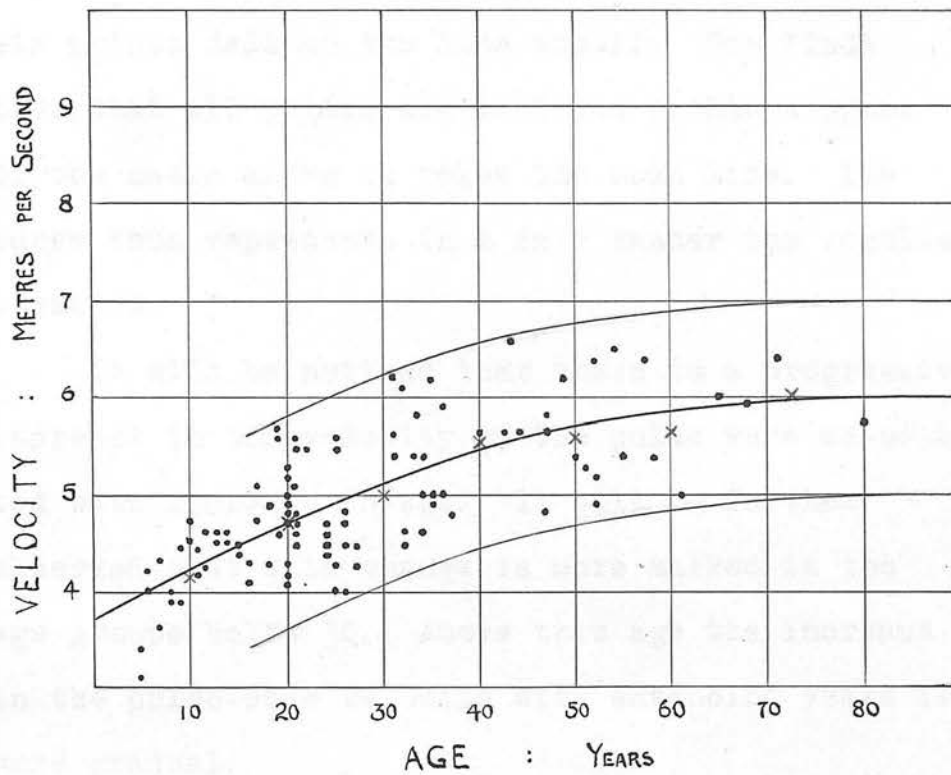
TABLE 13.SUBJECTS aged 65-80 Years.

| No.     | Age | Mean pulse-wave velocity<br>in metres per second |                  |              | Blood<br>pressure |
|---------|-----|--|------------------|--------------|-------------------|
|         |     | Brachial<br>artery                               | Radial<br>artery | Whole<br>arm |                   |
| 1       | 68  | 5.9  | 11.4             | 7.4          | 130/80            |
| 2       | 71  | 6.4  | 12.5             | 7.9          | 134/90            |
| 3       | 80  | 5.7  | 9.2              | 7.2          | 126/72            |
| Average |     | 6.0  | 11.0             | 7.5          | 130/80            |

# AGE AND PULSE-WAVE VELOCITY

IN

## BRACHIAL ARTERY



X POINTS OBTAINED FROM AVERAGES OF TABLES 7-13.

JSF

FIG. 36.

In Fig. 36, the relation between age and pulse wave velocity in the brachial artery is portrayed graphically. The mean line is drawn through these points in such a way that forty-eight points fall above the line, forty-nine points fall below and six points fall on the line itself. One finds then that all points are included within a space of one metre above or below the mean line. The curve thus represents in a fair manner the results obtained.

It will be noticed that there is a progressive increase in the velocity of the pulse wave associated with increase in age. It will be further observed that this change is more marked in the age groups below 30. Above this age the increase in the pulse-wave velocity with advancing years is more gradual.

In Fig. 37, the results obtained of the pulse wave velocity in the radial artery at different ages are similarly portrayed.

# AGE AND PULSE-WAVE VELOCITY

IN  
RADIAL ARTERY

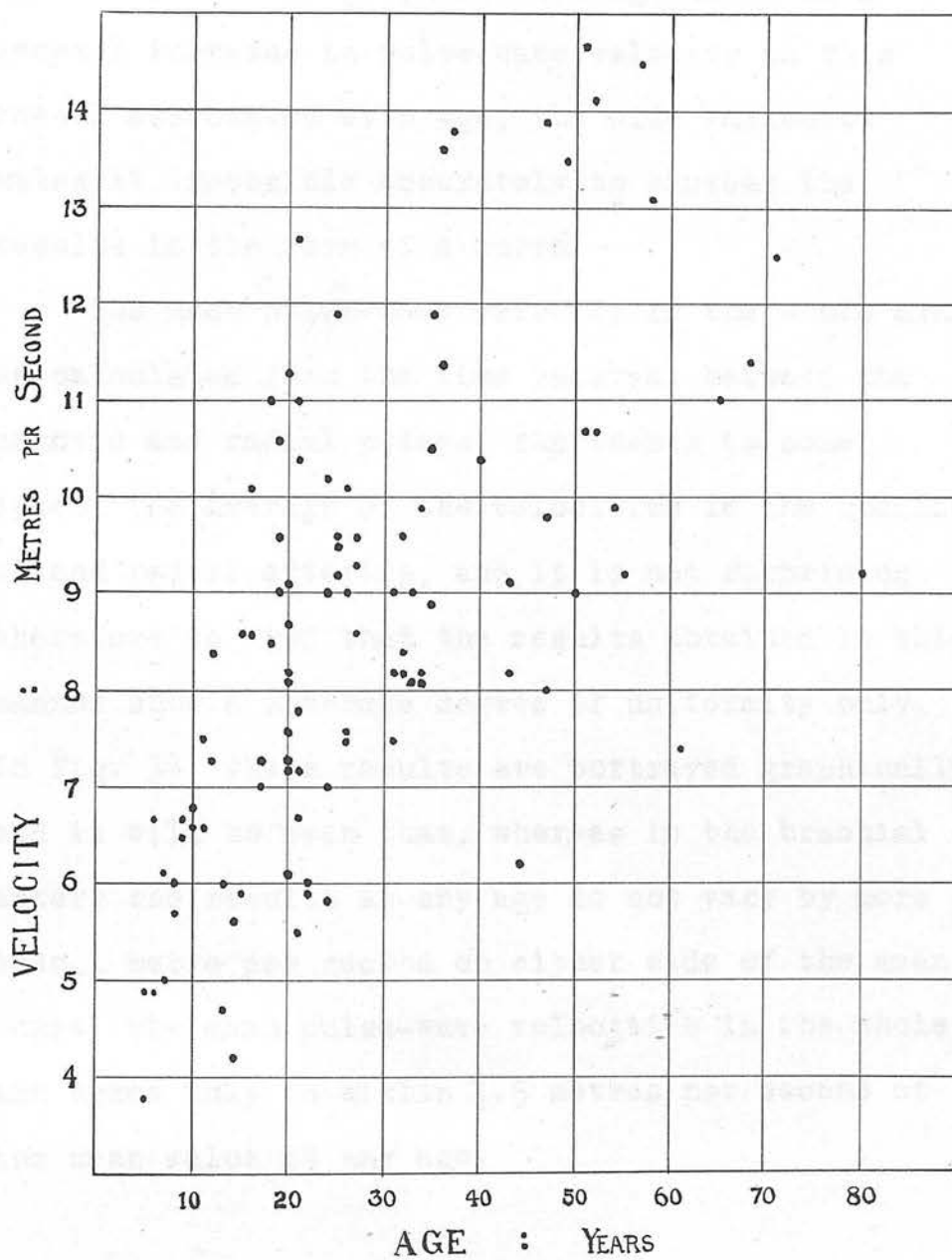


FIG. 37.

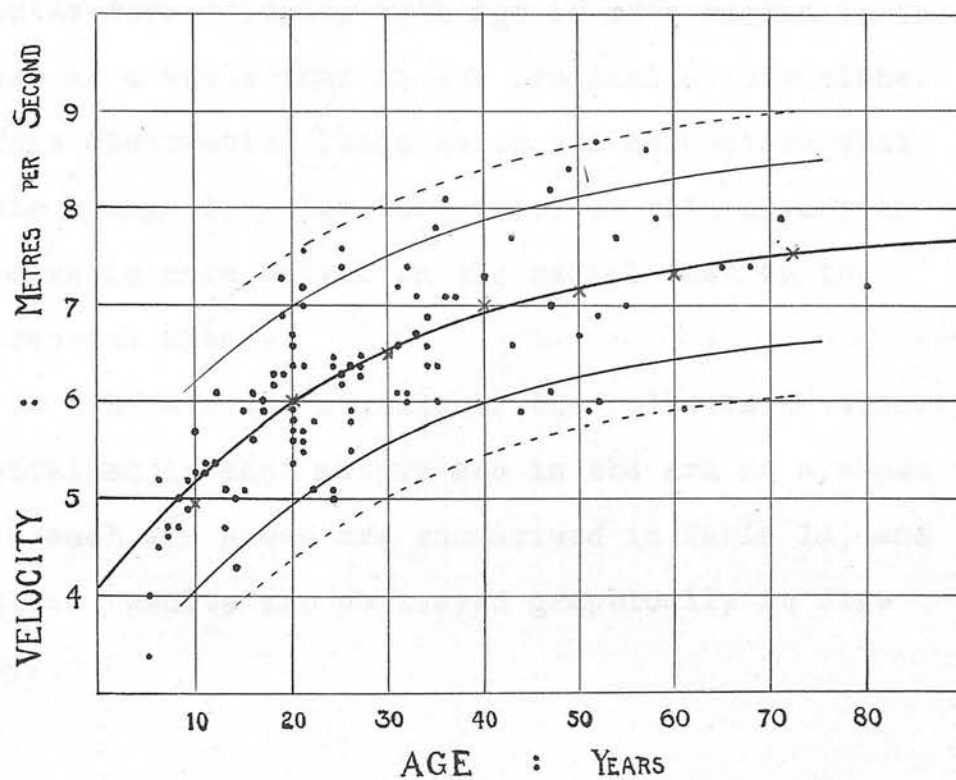
The wide variation of results obtained in this artery in subjects of approximately the same age is again manifest, and although there is a general increase in pulse-wave velocity in this vessel associated with age, the wide variation makes it impossible accurately to express the results in the form of a curve.

The mean pulse-wave velocity in the whole arm, as calculated from the time interval between the carotid and radial pulses, represents to some extent the average of the velocities in the brachial and radial arteries, and it is not surprising therefore to find that the results obtained in this manner show a moderate degree of uniformity only. In Fig. 38, these results are portrayed graphically and it will be seen that, whereas in the brachial artery the results at any age do not vary by more than 1 metre per second on either side of the mean curve, the mean pulse-wave velocities in the whole arm agree only to within 1.5 metres per second of the mean value at any age.

# AGE AND PULSE-WAVE VELOCITY

IN

WHOLE ARM



× POINTS OBTAINED FROM AVERAGES OF TABLES 7-13.

*J.S.F.*

FIG. 38.



The curve obtained is similar in type to that obtained from the brachial artery, but is, of course, placed at a higher level. The curve itself is slightly steeper indicating that the increase in pulse-wave velocity with age is more marked in the arm as a whole than in the brachial artery alone. This observation leads us to the assumption that the change in pulse-wave velocity with advancing years is more marked in the radial than in the brachial artery.

The average results of the pulse-wave velocity obtained in each artery and in the arm as a whole in each age group are summarised in Table 14, and these results are portrayed graphically in Fig.

39.

TABLE 14.SUMMARY OF AVERAGES - TABLES 7-13.

| Table | Ages  | Mean pulse-wave velocity<br>in metres per second |                  |              | Blood<br>pressure |
|-------|-------|--|------------------|--------------|-------------------|
|       |       | Brachial<br>artery                               | Radial<br>artery | Whole<br>arm |                   |
| 7     | 5-15  | 4.2  | 6.0              | 4.9          | 95/63             |
| 8     | 15-25 | 4.7  | 8.3              | 6.0          | 109/73            |
| 9     | 25-35 | 5.0  | 8.9              | 6.5          | 112/73            |
| 10    | 35-45 | 5.5  | 10.4             | 7.0          | 113/77            |
| 11    | 45-55 | 5.6  | 11.4             | 7.2          | 124/82            |
| 12    | 55-65 | 5.6  | 11.0             | 7.4          | 130/75            |
| 13    | 65-80 | 6.0  | 11.0             | 7.5          | 130/80            |

PULSE-WAVE VELOCITY IN THE ARTERIES OF THE ARM  
AT DIFFERENT AGES

(FROM AVERAGES OF TABLES 7-13.)

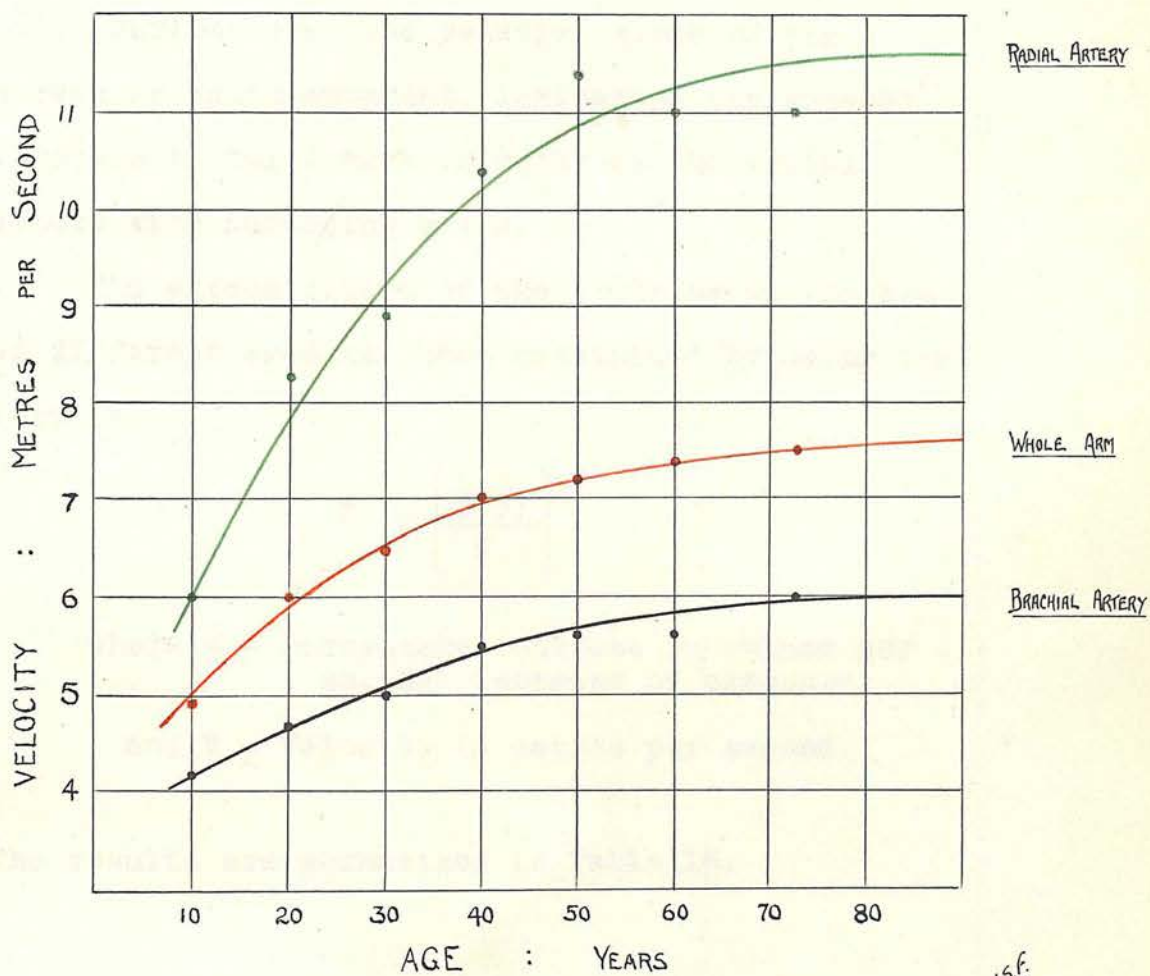


FIG. 39.

It is interesting to note that the curves obtained in this way bear a remarkable resemblance to those obtained in the ordinary way (Figs. 36 and 38). Furthermore, the relative slope of the curves is again apparent, indicating the greater increase in pulse-wave velocity in the radial artery with advancing years.

The extensibility of the arteries in the arm at different ages has been determined by using the formula:

$$E = \left[ \frac{3.57}{V} \right]^2$$

where E = Percentage increase in volume per  
mm. Hg. increase of pressure.

and V = Velocity in metres per second.

The results are summarised in Table 15.

TABLE 15.

MEAN EXTENSIBILITY OF ARTERIES  
IN DIFFERENT AGE GROUPS.

| Table | Ages  | Mean Extensibility |               |           | Blood pressure |
|-------|-------|--------------------|---------------|-----------|----------------|
|       |       | Brachial artery    | Radial artery | Whole arm |                |
| 7     | 5-15  | 0.70               | 0.35          | 0.53      | 95/63          |
| 8     | 15-25 | 0.57               | 0.18          | 0.35      | 109/73         |
| 9     | 25-35 | 0.51               | 0.15          | 0.30      | 112/73         |
| 10    | 35-45 | 0.42               | 0.12          | 0.26      | 113/77         |
| 11    | 45-55 | 0.40               | 0.10          | 0.24      | 124/82         |
| 12    | 55-65 | 0.40               | 0.11          | 0.23      | 130/75         |
| 13    | 65-80 | 0.38               | 0.11          | 0.22      | 130/80         |

From the figures so obtained it will be seen that over a period of sixty years, from 10 to 70 years of age, the extensibility of the brachial artery diminishes to about one half of its original value, while over the same period the extensibility of the radial artery diminishes to about one third.

These results are portrayed graphically in Fig. 40, and it will be seen that, whereas in the brachial artery the decrease in extensibility with years is more or less uniform, in the radial artery there is a rapid loss of extensibility in the early part of life, followed by a more gradual change from adolescence onwards.

MEAN EXTENSIBILITY OF ARTERIES  
IN  
DIFFERENT AGE GROUPS

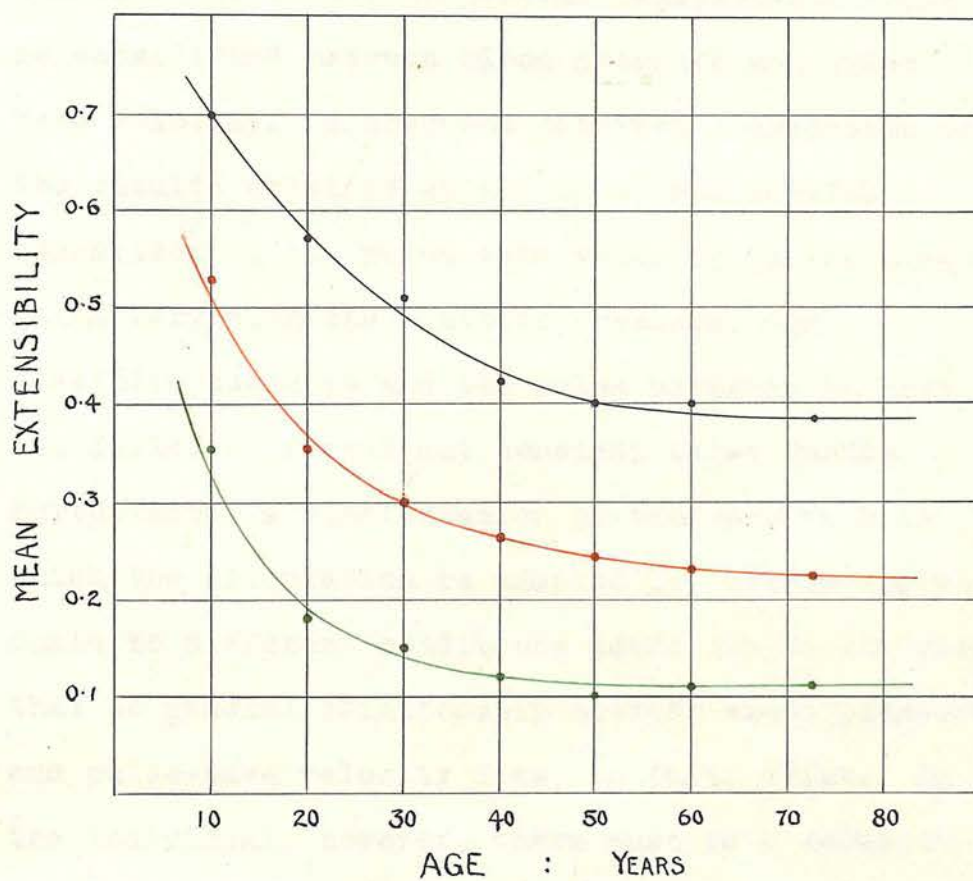


FIG. 40.



### BLOOD PRESSURE AND PULSE WAVE VELOCITY

Attention has already been drawn to the fact that in the group of normal subjects originally examined (Table 6), no general relationship could be established between blood pressure and pulse wave velocity. Subsequent detailed examination of the results obtained at all ages, and careful comparison of the pulse-wave velocity in the brachial artery with the systolic pressure, the diastolic pressure and the pulse pressure in turn, has failed to reveal any constant relationship. Furthermore, a consideration of the many ways in which the circulation is adapted in various individuals to different conditions leads one to the view that no general relationship between blood pressure and pulse-wave velocity does, in fact, exist. In the individual, however, there must be a relationship between the blood pressure and the pulse-wave velocity, and an alteration in pressure will produce a corresponding change in pulse-wave velocity, depending on the extensibility of the vessel wall and the pressure in the vessel.

Various methods have been devised whereby the blood pressure may be altered during life. Dawson, Higgins and Gorham (27-29) in experiments on dogs produced alterations in arterial pressure by nervous stimulation. The fact that these observers failed to obtain consistent results was probably due to the method, which almost certainly introduced complicating factors. In the human subject, drugs have been administered with a view to raising or lowering the arterial pressure, but by this means a general alteration in blood pressure is produced, and systemic effects, cardiac and vasomotor, are introduced, so complicating the result obtained.

Local alterations in blood pressure have been produced by applying pressure, either positive or negative, to the brachial artery by an armlet, but this method induces changes in the arterial pressure above and below the armlet. It is, in fact, extremely difficult to devise a method whereby the pressure in the vessels of the arm or leg may be varied without the introduction of complicating factors.

In order to compare the relative effects of change of pressure in the brachial and radial arteries, the pulse-wave velocity in these arteries was estimated with the arm in three different positions: first, held vertically up, then supported horizontally, and thirdly, hanging vertically down. By this means quite an appreciable alteration in blood pressure may be obtained which, in the first place, is a physiological change; secondly, it is for practical purposes a local effect, and, thirdly, it is not complicated by pressure effects from receivers or armlets applied with a view to the production of changes of pressure in the vessels.

The results obtained by this method in ten normal subjects of various ages are given in Table 16, from which it will be seen that the effect of alteration of posture and consequent alteration in blood pressure produces a more marked alteration in pulse-wave velocity in the radial artery than in the brachial artery.

The results are portrayed graphically in Figs. 41 and 42, and the more marked effect produced in the radial artery in comparison with the brachial artery is at once apparent, and indicates the much less extensible character of the former vessel.

TABLE 16.

## EFFECT OF CHANGE OF POSTURE OF ARM.

| No. | Age | Position of arm | Blood Pressure | Mean pulse-wave velocity in metres per second |               |           |
|-----|-----|-----------------|----------------|---|---------------|-----------|
|     |     |                 |                | Brachial artery                               | Radial artery | Whole arm |
| 1   | 14  | up              | 86/66          | 4.0   | 4.8           | 4.3       |
|     |     | horizontal      | 98/78          | 4.5   | 6.5           | 5.2       |
|     |     | down            | 112/86         | 5.0   | 12.1          | 6.9       |
| 2   | 17  | up              | 78/58          | 4.4   | 6.2           | 5.1       |
|     |     | horizontal      | 96/68          | 4.5   | 10.1          | 6.2       |
|     |     | down            | 102/78         | 4.7   | 17.2          | 7.4       |
| 3   | 20  | up              | 98/60          | 4.2   | 7.5           | 5.5       |
|     |     | horizontal      | 106/68         | 4.2   | 8.1           | 5.9       |
|     |     | down            | 122/94         | 4.4   | 11.1          | 6.6       |
| 4   | 20  | up              | 84/56          | 4.9   | 7.4           | 5.9       |
|     |     | horizontal      | 98/70          | 4.9   | 7.6           | 6.0       |
|     |     | down            | 112/80         | 5.0   | 10.2          | 6.9       |
| 5   | 21  | up              | 88/62          | 5.1   | 3.8           | 4.4       |
|     |     | horizontal      | 110/72         | 5.5   | 5.5           | 5.5       |
|     |     | down            | 122/84         | 6.0   | 16.1          | 8.7       |
| 6   | 32  | up              | 94/66          | 5.8   | 8.9           | 6.9       |
|     |     | horizontal      | 106/76         | 6.1   | 9.6           | 7.4       |
|     |     | down            | 122/86         | 6.6   | 10.0          | 7.9       |
| 7   | 34  | up              | 88/78          | 5.0   | 6.9           | 5.8       |
|     |     | horizontal      | 102/82         | 5.4   | 9.9           | 6.9       |
|     |     | down            | 118/92         | 5.5   | 12.9          | 7.7       |
| 8   | 35  | up              | 104/74         | 6.4   | 9.2           | 7.6       |
|     |     | horizontal      | 118/82         | 6.6   | 10.7          | 8.2       |
|     |     | down            | 124/92         | 6.8   | 12.0          | 8.8       |
| 9   | 57  | up              | 144/68         | 7.2   | 10.3          | 8.4       |
|     |     | horizontal      | 158/88         | 6.4   | 14.0          | 8.6       |
|     |     | down            | 168/104        | 6.9   | 15.7          | 9.4       |
| 10  | 58  | up              | 112/66         | 5.9   | 10.2          | 7.7       |
|     |     | horizontal      | 120/78         | 5.4   | 13.1          | 7.9       |
|     |     | down            | 128/90         | 5.8   | 14.3          | 8.2       |

DIAGRAM SHOWING  
EFFECT OF CHANGE OF POSTURE OF ARM

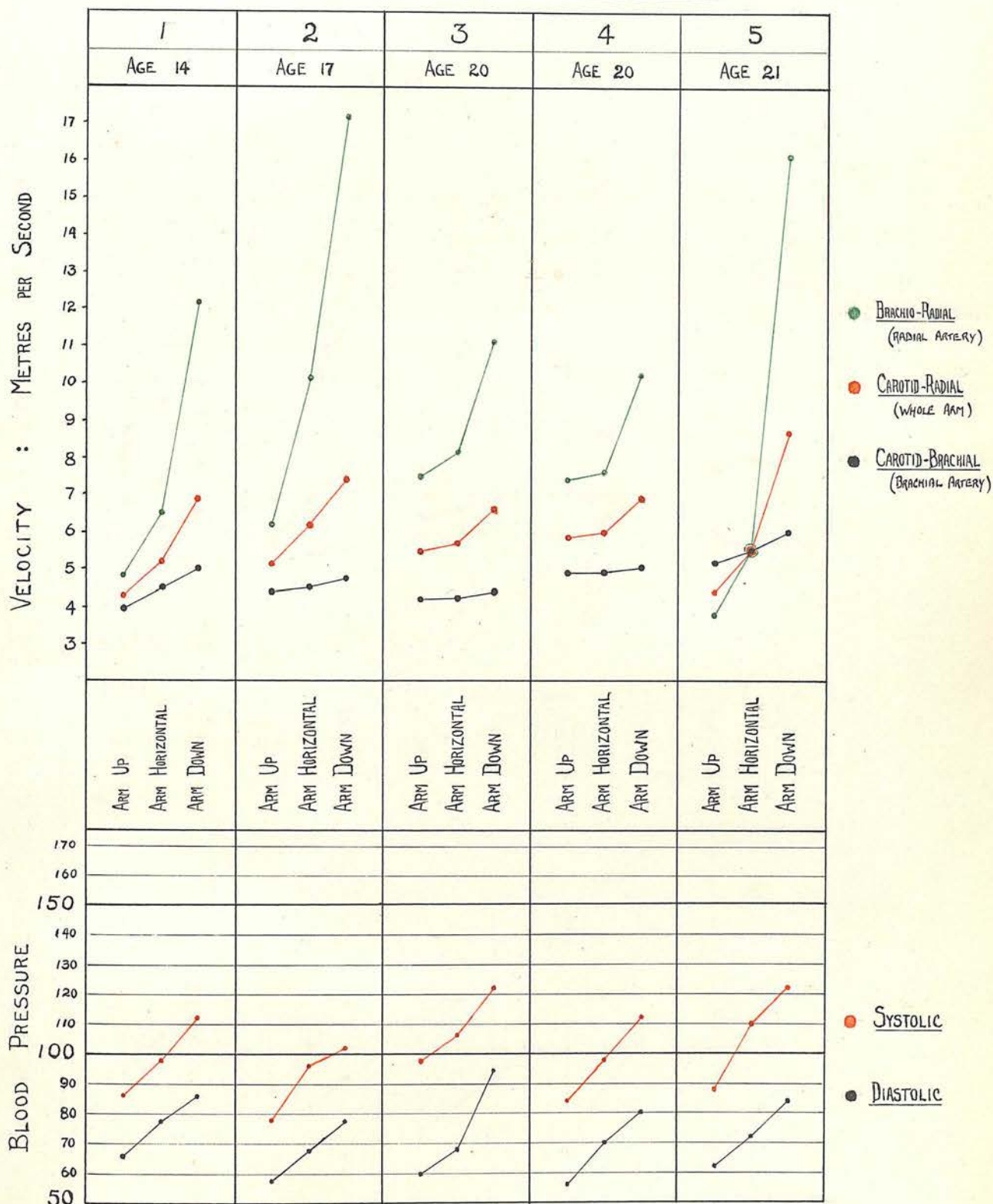


Fig. 41.

J.S.F.



DIAGRAM      SHOWING  
EFFECT OF CHANGE OF POSTURE OF ARM

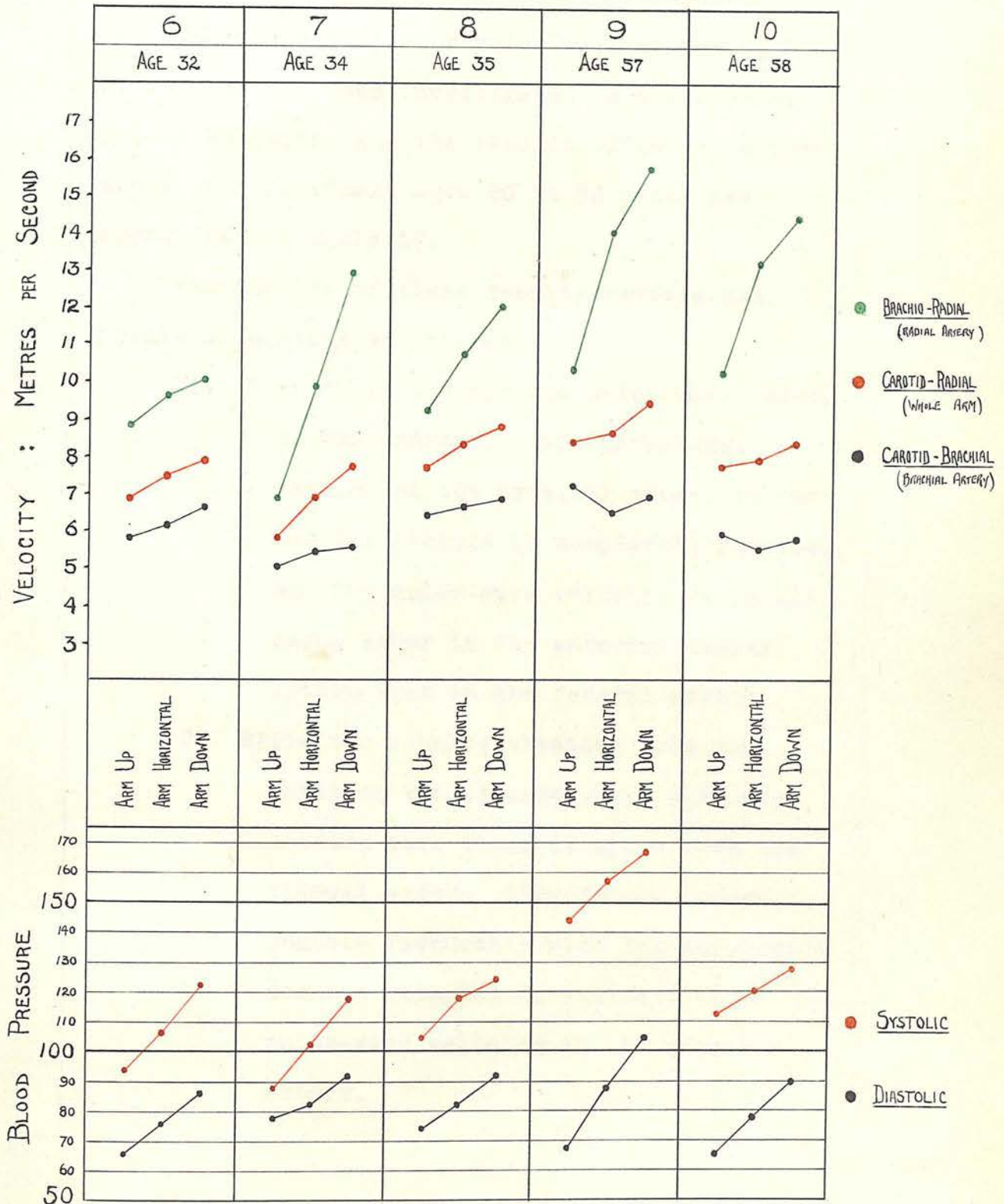


FIG. 42.

### PULSE WAVE VELOCITY IN THE LEG

The velocity of the pulse wave in the arteries of the leg has been investigated in a number of normal subjects, and the results of twenty experiments on individuals aged 20 to 34 years are summarised in Table 17.

Examination of these results reveals two points of particular interest:

- (1) Whereas in the arm the pulse-wave velocity was greater in the peripheral portion of the arterial trunk, in the leg the picture is completely reversed, and the pulse-wave velocity is in all cases lower in the anterior tibial artery than in the femoral artery.
- (2) While the results obtained from the anterior tibial artery are much more uniform than those obtained from the femoral artery, they do not, however, compare favourably with the consistent results obtained in estimations of the pulse-wave velocity in the brachial artery.



TABLE 17.

RESULTS OF PULSE-WAVE VELOCITY  
in  
LOWER LIMB

| No. | Age | Mean pulse-wave velocity<br>in metres per second |                      |              |
|-----|-----|--|----------------------|--------------|
|     |     | Femoral<br>artery                                | Ant.Tibial<br>artery | Whole<br>leg |
| 1   | 20  | 12.9   | 6.6                  | 9.2          |
| 2   | 20  | 22.0   | 6.8                  | 10.2         |
| 3   | 20  | 10.2   | 7.7                  | 9.7          |
| 4   | 20  | 15.4   | 7.1                  | 9.6          |
| 5   | 21  | 13.2   | 8.0                  | 10.0         |
| 6   | 21  | 14.9   | 7.9                  | 11.2         |
| 7   | 21  | 17.1   | 9.3                  | 11.7         |
| 8   | 21  | 11.3   | 7.9                  | 9.4          |
| 9   | 22  | 21.6   | 8.4                  | 11.3         |
| 10  | 24  | 14.8   | 5.7                  | 8.2          |
| 11  | 24  | 26.6   | 9.6                  | 13.3         |
| 12  | 25  | 11.5   | 8.4                  | 9.7          |
| 13  | 26  | 15.4   | 7.8                  | 11.0         |
| 14  | 27  | 15.1   | 9.3                  | 12.0         |
| 15  | 31  | 10.0   | 8.4                  | 9.0          |
| 16  | 32  | 15.3   | 7.9                  | 10.9         |
| 17  | 32  | 24.4   | 7.8                  | 11.9         |
| 18  | 33  | 15.2   | 8.0                  | 9.7          |
| 19  | 34  | 15.6   | 7.8                  | 10.3         |
| 20  | 34  | 20.2   | 9.7                  | 13.6         |

SUMMARY

|                  |      |     |      |
|------------------|------|-----|------|
| Minimum          | 10.0 | 5.7 | 8.2  |
| Maximum          | 26.6 | 9.7 | 13.6 |
| <u>Variation</u> | 8.3  | 2.0 | 2.7  |

As will be seen later, the explanation of these phenomena is to be found in the varying structure of vessels concerned and the different pressures at which they function.

In view of the wide variation in the results obtained, it is doubtful whether data of the pulse wave velocity in the arteries of the leg would be of any clinical value, even if obtained from a large number of subjects, and for this reason no extensive investigation has been undertaken.

VOLUME ONE

— oOo —

SECTION

FOUR

— oOo —

## HISTOLOGICAL

## INVESTIGATION

Introduction.

Source of material.

Method of fixing.

Method of staining.

Photo-micrography.

Conclusions.

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## HISTOLOGICAL INVESTIGATION

From a survey of the literature on the subject of arterial structure, it would seem that no extensive investigation of the varying structure of different arteries has been undertaken, and of the relationship between function and structure.

It would appear to be accepted by all that in order to relieve the heart of strain, the arteries in proximity to that organ are extremely elastic in structure, while very few fibres of elastic tissue are found in the peripheral vessels.

Jaques, Poirier and Charpy (71) have classified the arteries and suggested two main groups: (a) the elastic type, of which the aorta, subclavian and carotid artery are examples, and (b) the muscular type, such as the radial and lingual artery. The axillary and common iliac arteries are described as being transitional in type.

Kölliker (75) describes the arteries as being composed of three coats: an inner elastic coat consisting of a more or less well defined layer of elastic tissue covered internally by a layer of

endothelial cells, varying in thickness in different arteries and in some cases separated from the elastic membrane by a fine layer of connective tissue; a middle coat consisting mainly of concentrically disposed plain muscle fibres interwoven with elastic tissue fibres, and in the larger vessels near the heart consisting almost entirely of concentric elastic fibres; and an outer coat which is composed chiefly of connective tissue, but contains a varying amount of elastic tissue, the fibres of which are fenestrated and arranged chiefly in the area immediately adjoining the middle coat.

The structure, origin and growth of the internal elastic coat has recently been investigated by Wolff (125), who in a series of observations on the external iliac artery of infants and adults indicates the progressive development with age of successive layers of elastic tissue in the sub-endothelial layers of the blood vessels, to which he applied the term 'pseudo-elastic'.

The structure of the middle coat in different arteries has been studied by Sslowjew (111). This



observer has investigated the structure of the aorta from a number of subjects of different ages, and has shown that in this vessel there is variation in structure corresponding to the age of the subject.

According to Schäfer (110) the external coat of the aorta is very thin, and this view is supported by the recent work of Dubreuil and Escudier-Donnadieu (31). These observers have shown that, in the large vessels, the external coat exists only to a very small degree. It becomes more marked in the medium sized vessels, diminishing again towards the periphery, and in the smaller arteries existing only as a thin layer of annular fibres.

The present investigation has been undertaken in an attempt to correlate, if possible, the experimental results obtained in the different arteries with the histological structure of corresponding vessels.

A large number of vessels from subjects of different ages has been examined histologically,



and sixty-three photo-micrographs are reproduced in Volume II to illustrate the various points.

#### Source of Material.

The arteries have been obtained from subjects in various post mortem rooms, and the investigation has been limited to those subjects in whom death occurred as a result of accident or following an acute illness not likely to produce immediate arterial changes. The examination does not include vessels from any subject in whom any obvious evidence of arterial disease was detected.

#### Method of Fixing.

The vessels on removal were transferred directly to a 10 per cent. solution of formol saline, where they were allowed to harden for three or four days, after which they were embedded in paraffin and cut in the usual way.

No attempt was made to submit the vessels to any given internal pressure during the process of fixation, and while it is appreciated that for this reason no accurate comparison between different

individuals is possible; in the case of arteries removed from the same individual, similar conditions of post mortem rigidity and contraction are present and a comparison between different portions of the arterial tree in the same subject is thus permissible.

#### Method of Staining.

The stain used was a modification of Virhoeff's elastic tissue stain described by Mallory and Wright (87).

The stain was kept in three solutions:-

#### Solution No.1.

|                       |     |
|-----------------------|-----|
| Haematoxylin crystals | 4   |
| Absolute alcohol      | 100 |

#### Solution No.2.

10% aqueous solution of  
ferric chloride.

#### Solution No.3.

|                  |     |
|------------------|-----|
| Iodine           | 2   |
| Potassium iodide | 4   |
| Water            | 100 |

For use the solutions were freshly mixed in the proportions of two parts of solution No. 1 and one part each of solutions 2 and 3.

The stain was applied until the section was perfectly black; this usually required from fifteen to thirty minutes. Differentiation was then carried out in a 2 per cent. aqueous solution of ferric chloride. This process requires a few seconds only, but may conveniently be controlled by repeated washing and examination under low power. If the differentiation is carried too far, the section may be re-stained, provided it has not been treated with alcohol.

After differentiation the section was washed in water, then treated with 95 per cent. alcohol to remove the remnants of the staining due to the iodine solution. After further washing for about five minutes in water, the section was dehydrated and mounted in the usual way.

#### Photo-micrography.

Ilford ortho-chromatic backed plates were employed, and illumination was supplied by a small arc lamp with a condensing lens and a green filter.

The apparatus was carefully calibrated by means of a micrometer slide before each batch of



photographs was taken, and a uniform magnification of 100 diameters was employed throughout except in the case of the foetal arteries, which were taken with a magnification of 200 diameters.

The black surround to the photo-micrographs was obtained by using two masks in conjunction with a double printing process, the picture and the surround receiving separate and different exposures.

#### CONCLUSIONS

- (1) The large vessels show a greater degree of elasticity in structure in the sections of the artery nearer the heart.
- (2) In all the subjects examined the brachial artery exhibited a greater degree of elasticity in structure than the radial artery.
- (3) In the case of the child and the foetus, the difference in structure between the brachial and radial artery did not appear to be so marked as in the adult subjects.

- (4) In the brachial artery there is a progressive decrease in the amount of elastic tissue present, the more proximal portion exhibiting the greatest elasticity in structure.
- (5) The femoral artery presents a less elastic structure than the brachial artery.
- (6) While in the arm the different sections of the arterial branch show a variation in structure, in the lower limb the different sections of artery present a similar appearance in regard to structure.
- (7) While it is held by some observers that the strength of an artery depends largely on the outer coat, and that this coat serves to resist undue pressure from within, it is of interest to note that in the large vessels, which during exercise are called upon to withstand very considerable pressure, this layer is noticeably deficient. It is, however, well marked in the vessels of the limbs, and the fact that in this coat the elastic fibres run mainly longitudinally

would appear to indicate that the function of the external coat is one of accommodation to the alteration in length of the artery in different postures of the limb.

VOLUME ONE

— oOo —

SECTION

FIVE

— oOo —



## DISCUSSION

### THE PULSE WAVE.

### THE FUNCTION OF THE ARTERIES:

- (a) Arterial function and the heart.
- (b) Arterial function and the capillary circulation.

### THE EXTENSIBILITY OF THE ARTERIES:

- (a) Varying extensibility of different arteries.
- (b) Factors influencing the extensibility of the arteries.
  - (i) The influence of structure.
  - (ii) The influence of blood pressure.

### CLINICAL APPLICATION.

### SUMMARY AND CONCLUSIONS.

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## DISCUSSION

### THE PULSE WAVE

In order to appreciate fully the circulatory function, it is necessary to have a definite conception of the nature and significance of the pulse wave and the method of its propagation.

It must be clearly appreciated that the pulse wave does not represent a volume of blood which has been ejected into the arteries by the heart, and which passes along the arterial tree as a mass of blood. The impulse is not due to the actual passage of blood along the artery, but represents a wave of pressure which is transmitted to the arterial wall by the blood stream.

When the ventricle contracts, blood is forced into the aorta and, as a result of the increase in volume of blood, the pressure within the vessel rises. This increase of pressure may be exerted in one of two ways: (a) in driving the column of blood in the arteries forward, or (b) in distending the vessel wall. Since the resistance to forward

movement of the large column of blood in the arteries is considerable, and as the normal healthy aorta is highly elastic in structure, the energy generated by the ventricle is largely utilized in distending the aorta, being converted into potential energy in the stretched arterial wall. With the cessation of the ventricular contraction, the energy stored in the arterial wall is gradually expended and the initial rise in pressure in the aorta is maintained to an extent which depends on the amount of energy which the vessel wall has been capable of storing by virtue of its elastic properties. The wave of pressure which has thus been brought about by the contraction of the ventricle is transmitted to the periphery from segment to segment along the arterial tree in a manner analogous to that seen when a locomotive begins to push a chain of trucks, the original impulse being transmitted as a wave successively from one truck to the other.

The terms 'elasticity' and 'extensibility' which are frequently employed must be clearly

differentiated. While elasticity refers to structure only, the property of extensibility is dependent both on structure (i.e. elasticity) and blood pressure.

In the passage of the pulse wave, pressure is exerted on the vessel, which distends accordingly in proportion to its elastic properties. It will readily be appreciated therefore, that where the vessel wall is relatively elastic and consequently more extensible, distension occurs as a result of the rise in pressure, and only when a certain degree of distension has been reached is the pressure wave transmitted to the segment below. When, on the other hand, the vessel wall is inextensible, the pressure wave is rapidly transmitted between adjacent segments and the pulse wave is rapidly propagated towards the periphery.

The rate of transmission of the pulse wave, therefore, has a definite relationship to the extensibility of the artery, and we have seen how these two functions have been related by various observers, the velocity being inversely proportional to the square root of the extensibility.

## THE FUNCTION OF THE ARTERIES

It would be unreasonable to regard the arteries merely as conducting tubes: the aorta and the larger arteries undoubtedly function as elastic reservoirs, relieving the strain on the heart and helping to maintain a uniform supply of blood to the periphery.

### Arterial function and the heart.

Poirier (99) has pointed out that the diminution in the calibre of the arch of the aorta throughout its course is not proportional to the size of the branches which arise from it, and Sainsbury (109) and others have drawn attention to the fact that the calibre of the aortic arch is excessively large when compared with the capacity of the left ventricle. The aorta is thus not merely a delivery tube but an elastic reservoir relieving the heart of strain and preventing sudden changes of pressure in the peripheral circulation.

Wiggers (124) has shown by animal experiment that the pressure in the aorta rises only during



the earlier phase of ventricular systole, and, at rest, this period occupies only one third of the whole cardiac cycle. The aorta is therefore distended rapidly and the process of retraction is much more gradual. This applies to all the arteries of the body, the phase of distension being short in comparison with the time occupied by the artery in resuming its normal calibre. In this manner each section of artery helps to reduce the distension of the section proximal to it, by distending in response to an increase in pressure and rapidly providing accommodation for a quantity of blood which can subsequently be slowly distributed to the periphery. By thus accommodating the sudden increase in volume, following the ventricular systole, the arterial system relieves the heart of strain. It follows, therefore, that the efficiency of the arteries depends to a very large degree on their extensibility: the more extensible are the arteries, the smaller will be the pressure required to produce a given increase in their volume, and as Rohde (102-104) has shown that the energy expended by the heart is proportional to the

pressure developed, the effort which the heart is called upon to make in expelling its contents will vary inversely with the extensibility of the arterial walls.

#### Arterial function and the capillary circulation.

The importance of the capillary circulation cannot be overestimated, as it is there that the vital processes essential to life are carried on. For this reason it is of the utmost importance that the capillary circulation should be maintained with the highest possible efficiency under the constantly varying conditions to which it is subjected. It is for this fundamental purpose that the whole circulatory mechanism exists and the various components are subservient to this one object.

Considered from the point of view of supply of blood, the efficiency of the capillary circulation demands that this should be adequate and uniform; a certain quantity of blood must pass through the capillary area in a given time and at a certain rate. The supply of blood must be adequate to meet the requirements of the tissues: if it is



inadequate, anoxaemia will result; if it is excessive, the heart will be called upon to do unnecessary work. Furthermore, the rate of flow must be such that the exchanges between the blood and the tissues can be most efficiently carried out. For a given rate of blood flow per minute, the more uniform the rate of circulation in the capillaries, the more efficiently will the chemical exchanges between the blood and the tissues be conducted. In order to secure this uniformity of flow, it is obvious that the difference between systolic and diastolic pressure must be at a minimum - in other words, there must be a low constant pulse pressure, and it is in the attainment of this object that the arteries function by reason of their extensibility. The greater the extensibility of the arteries, the smaller will be the increase in pressure (in pulse pressure) required to produce a given increase in their volume. Similarly, during the period of arterial retraction, the more extensible the arteries, the greater will be the potential energy in the stretched arterial wall at the end of ventricular systole, and consequently the smaller

will be the fall in pressure for a given decrease in volume. The greater the extensibility of the arteries, therefore, the more uniform will be the flow of blood through the capillary circulation.

#### THE EXTENSIBILITY OF THE ARTERIES.

We have seen that both from the point of view of the heart and the capillary circulation, the greater the extensibility of the arteries, the more efficient will be the arterial mechanism. This property of extensibility, however, even in the normal subject is not uniform throughout the arterial system, and it has been shown that certain arteries are normally more extensible than others. From the point of view of relieving the strain on the heart, one would expect to find the larger arteries in proximity to the heart relatively more extensible than the smaller peripheral vessels. This view is supported by the results obtained in estimations of pulse-wave velocity in the brachial and radial arteries. It has been shown that in the arm the extensibility of the more proximal section of the arterial trunk is greater than the distal

portion. The histological investigation is in agreement with this finding, as the brachial artery exhibits a definite elastic structure which is more marked in the upper portion, while the radial artery contains very few elastic fibres in its wall. In addition, it has been shown that while both the common carotid and external carotid artery contain a large number of elastic fibres, the elasticity in structure of the former vessel is relatively greater than that of its more distal continuation. Again, the femoral and anterior tibial artery, which are situated some distance from the heart, are both relatively inelastic in structure when examined microscopically, and both vessels exhibit a relatively low degree of extensibility as estimated by the velocity of the pulse wave. In this connection, however, it must be borne in mind that the blood pressure in the leg is greater than in the arm, as Bazett (4) and Burdick (22) have already indicated. Furthermore, Hill and Flack (66) have shown that in the arteries of the lower limb, the blood pressure is considerably greater in the erect posture than when the subject is lying down:

differences in systolic pressure of 60 to 70 mm. having been found by these observers. These facts have been confirmed by repeated estimations of blood pressure in a number of normal subjects in different postures. Erlanger and Hooker (38) have investigated the relationship between blood pressure and posture, and these observers are of opinion that the changes which occur are due mainly to the effect of gravity. If the arteries of the lower limb were of an extensible character, the dilatation which would result from the increase in pressure on assuming the erect posture would have a marked effect on the circulation as a whole, since the volume of blood in the limbs would be considerably increased. It is not surprising, therefore, to find that in the lower limb where the vessels have to withstand relatively high blood pressures, which vary considerably, the arterial wall is thick and relatively inextensible.

It is of interest to note that while the anterior tibial artery was found by experiment to be more extensible than the femoral artery, histological investigation did not reveal a corres-

ponding difference in structure, and both vessels presented a similar appearance in regard to the amount of elastic tissue present. From the experiments of Roy (106) and subsequent observers, we know that, other factors being equal, the extensibility of an artery varies inversely with the internal pressure, thus if the structure of the vessel wall is in both cases similar, the blood pressure in the anterior tibial artery must be lower than that in the femoral artery. Findlay (42), who has investigated blood pressure at different points of the circulation, found that in children systolic pressure was uniform at different points of the circulation, but that in adults systolic pressure was lower at the periphery, and that the difference between central and peripheral systolic pressures increases with age. Similar observations in the subjects examined has revealed not only a fall in systolic pressure, but a diminution both in diastolic pressure and in pulse pressure. The low degree of elasticity of the vessel wall is thus compensated by the lower blood pressure in the peripheral circulation, which



allows the vessel to function at a pressure permitting a greater degree of extensibility, thus smoothing out the pressure wave before it reaches the capillary circulation.

Factors influencing the extensibility of the arteries.

The degree of extensibility of an artery in the living subject depends not only on the structural constitution or elasticity of the vessel wall, but on the functional conditions to which it is subjected at the moment. Of the latter, the most important is the pressure of the blood within the artery, but such factors as alterations in the viscosity of the blood and changes in the tone of the vessel wall as a result of its muscular structure cannot be ignored. In the smaller arteries, it is possible that the muscular element may be of importance, but in the larger vessels it is unlikely that the small amount of muscular tissue present is able to exert any considerable influence at the pressures existing normally during life.



The viscosity of the blood has been shown by Murray Lyon (86) to vary between 50 and 200 per cent. of the normal in pathological conditions, but variations of this extent will have a relatively small effect on the extensibility of the vessel wall.

The influence of structure on extensibility.

It has been shown that the different degrees of extensibility which have been found in the various vessels bear a definite relationship to the histological structure of the arteries concerned. This is seen particularly clearly in the arm, where the difference in structure between the two sections of artery is well marked. While the blood pressure in the more proximal segment is slightly greater, this factor is outweighed by the more elastic structure of the vessel in its proximal part, and a greater degree of extensibility is exhibited.

While the extensibility of the different arteries has been shown to decrease with age, it has been pointed out by Wild (125), Gallavardin (50) Thomson (113) and others that the diastolic blood

pressure shows little tendency to increase with age. It is probable therefore that the decrease in extensibility with age is in large measure due to a diminished elasticity in the structure of the vessel wall and, in lesser degree, to the slight increase in diastolic pressure.

In certain wasting diseases the elastic element of the arterial wall loses its efficiency, and the extensibility of the vessel is consequently impaired. An example of such a condition was cited by Roy (106), the artery in question being obtained from an extremely emaciated dog. Similar results have been obtained by Bramwell, Downing and Hill (12) in their experiments on excised human carotid arteries.

On the other hand, in calcareous arteries, the stiffening of the vessel wall is due not only to an impaired efficiency of the elastic element, but to the deposition of new material which is non-elastic. In such conditions therefore, the decrease in extensibility is still more marked, and Munzer (92) and others by observations on the pulse-wave

velocity in living subjects have shown that there is a marked decrease in the extensibility of the vessel wall in cases of arterio sclerosis.

The effect of calcification and contraction of the vessel wall in relation to blood pressure estimations has been considered in detail by many observers: the investigations of Russel (108), Stevenson (112), McWilliam (95, 96) and Kesson (74) have emphasised the importance of these factors. It is probable that the higher systolic pressure readings obtained in the leg by Hill and others (67, 68) in cases of arterio sclerosis were due not, as they suggested, to a better conduction of the systolic pressure, but to a water hammer action consequent on the more rapid propagation of the pulse wave in the rigid arteries.

The influence of blood pressure on extensibility.

It has been shown by Bramwell, Downing and Hill (12) in experiments on excised vessels that at low pressures the rate of transmission of the pulse wave remains fairly constant, but as the internal pressure reaches the normal diastolic value, the

pulse-wave velocity rises rapidly and the extensibility diminishes proportionately. If this is true in the living subject, a slight rise in diastolic pressure will be associated with a considerable diminution in arterial extensibility and a correspondingly great increase in the amount of energy which the heart will be called upon to expend in maintaining its output.

Observations on isolated arteries, however, are open to the criticism that post mortem changes may have taken place in the vessels, and the results cannot be compared directly with those obtained in living arteries which are probably in a different state of tone during life.

Various attempts have therefore been made to investigate the relationship between blood pressure and extensibility during life. It has been shown that there is an alteration in blood pressure associated with respiration, and the effect of this on the extensibility of the arteries of the arm has been investigated. It has been found that the relatively elastic portion of the arterial branch, namely the brachial artery, is affected to a lesser

degree than the more inextensible radial artery. A similar reaction has been demonstrated when the pressure in the vessels was altered by changing the posture of the arm, the relatively inextensible radial artery exhibiting a much greater fall in extensibility than the brachial artery when subjected to a rise in pressure.

These findings are thus in general agreement with the observations on excised vessels. The more inextensible the artery, the greater is the decrease in inextensibility for a given rise of pressure, and the greater will be the strain on the circulation above this point and so ultimately on the heart. Furthermore, the importance of a high degree of extensibility in the more proximal sections of the arterial tree is at once apparent, a reasonable degree of extensibility requiring to be preserved in spite of variations in blood pressure, in order that the strain on the heart may be kept as low as possible.

Attempts have been made by various observers to associate blood pressure and extensibility in a general way. Laubry, Mougeot and Giroux (79), and



Beyerholm (8) have found a general relationship between blood pressure and carotid-radial pulse-wave velocity. Bramwell and Hill (40) found a relationship between results of the carotid-radial pulse-wave velocity obtained in living subjects and the velocity of the pulse-wave in excised carotid arteries. Bazett and Dreyer (5) also found an agreement between their estimations of the pulse-wave velocity in the arm and the results obtained by Bramwell and Hill (13) in excised carotid arteries.

These facts are surprising in view of the different structure of the vessels concerned, but the relatively limited range of blood pressure available in the subjects examined and the limited degree of uniformity obtained do not carry conviction.

Considerable variation in structure, particularly in regard to the amount of elastic tissue present, has been shown to exist in different arteries. Furthermore, there is a gradient in structure, the transition from the highly elastic to the inelastic portion being a gradual process



with intermediate degrees of elasticity in sections of artery between.

A correlation has been established between the histological structure and the extensibility, the vessels of more elastic structure exhibiting a greater degree of extensibility.

If the structure remain constant, there is a definite relationship between blood pressure and extensibility. This has been shown by other observers in their experiments on excised vessels, in which pressure and extensibility were correlated in each separate portion of artery by producing alterations of pressure within the lumen. For each experiment, therefore, the structure remained constant, and it was shown that with a difference in the structure, a given internal pressure was associated with a different degree of extensibility.

In the living subject, apart from alterations in the tone of the vessel wall as a result of intrinsic muscular contraction, the structure may be assumed to be constant in the individual, and in the present investigation the relationship between blood pressure and extensibility has been examined

by comparing the extensibilities at the different pressures brought about by respiratory movements and by alterations in posture of the limb. It has been shown that while in the individual a certain rise in pressure was associated with a certain decrease in extensibility, in a different subject a similar alteration in pressure might produce a greater decrease in the extensibility, indicating the presence of another factor, namely structure.

Similar results were obtained by Bramwell, McDowall and McSwiney (17) and Hemingway, McSwiney and Allison (60). These observers, by varying the pressure in a hollow rubber bandage applied round the arm, were able to alter the effective pressure in the section of artery under the bandage. In their calculations, however, they assume that the rate of propagation of the pulse wave above and below the applied bandage is unaffected by the applied pressure. The experiments outlined in Table 1 have shown this assumption to be erroneous, but while the actual figures obtained are subject to revision, the effect of structure in modifying

the relationship between pressure and extensibility is clearly seen and cases are grouped as hyper-extensible, normal and hypo-extensible, according to their reactions to different applied pressures.

It has been shown that there is a progressive decrease in extensibility, both in the brachial and in the radial artery, with age. Taken in conjunction with the slight increase in diastolic blood pressure, which is commonly known to occur with advancing years, this fact may to some extent explain the general relationship between blood pressure and extensibility which has been found by other observers.

Fisher (43) has shown that blood pressure may vary considerably in the same individual within a few seconds, without any exciting cause being apparent. In subjects of the same age, while consistent results have been obtained in estimations of the pulse-wave velocity, the blood pressure, as is commonly known, varies normally in different individuals within considerable limits.

Thus, an elderly person with a normal degree of arterial extensibility may have a relatively low blood pressure for his years, while a younger subject may have the same blood pressure and exhibit a much greater degree of arterial extensibility. Similarly it has been shown that two subjects of the same age may have the same degree of arterial extensibility while one has a relatively high, and the other a relatively low blood pressure.

The chief factors which determine the extensibility of a vessel are the structure of the wall and the blood pressure. It has been shown that if the structure remain constant, an alteration in the blood pressure is followed by an alteration in the extensibility. Similarly it may be argued that if the blood pressure remain constant, an alteration in structure will be associated with an alteration in extensibility.

The extensibility of a vessel thus depends not on blood pressure alone, but is a function of blood pressure and structure. It will readily be appreciated, therefore, that any attempt to relate

blood pressure to extensibility without taking into account the factor of structure can have no justification.

#### CLINICAL APPLICATION

In the study of the circulation it would appear that the more complex cardiac mechanism has absorbed the interest of investigators, and the apparently simple function of the arterial system has largely escaped attention. In consequence of this, little accurate data is available of the extent to which the functional efficiency of the arterial wall is affected by different physiological and pathological conditions, and of the relationship between this function and the circulatory mechanism as a whole.

From the point of view of the work of the heart and the capillary circulation, it has been shown that the efficiency of the arterial system depends largely on the extensibility of the vessels, and a means of investigating this function with accuracy in the living subject must therefore be

of clinical value.

It has been shown that the primary factors involved in the arterial mechanism are blood pressure, structure and extensibility, and that these three factors are functions of one another.

We have at our disposal in the commonly used sphygmomanometer a method whereby, for clinical purposes, the blood pressure may be determined with a reasonable degree of accuracy. Apart, however, from the rough indication of extensibility furnished by a study of the pulse pressure, estimations of blood pressure cannot furnish us with accurate information of the other two factors. By investigating the rate of propagation of the pulse wave, however, in different sections of the arterial system, and calculating from this the degree of extensibility present, we are able from a comparison of the two factors of blood pressure and extensibility to arrive at a definite opinion with regard to structure.

An additional means is thus provided for the differentiation between various forms of hypertension and hypo-tension. Furthermore, by



comparison with the normal, changes in the structure of the vessel walls may be estimated quantitatively.

By comparing the time of arrival of the pulse wave at different points of the circulatory system, localised arterial disease may be detected. It is probable that an investigation of the pulse-wave velocity would indicate the presence of aneurysm at a very early stage in its development, and by comparing the time intervals of the pulse wave at points on the same side and on opposite sides of the body, the site of the lesion may be determined.

In the correlation between age and extensibility which has been established, it must be realised that the normal subjects investigated included individuals from different spheres of life, students, laboratory assistants, and labourers.

It is probable that the curve relating pulse wave velocity to age, which was obtained from subjects both of sedentary and active habits, is fairly representative of the normal individual, and that in the case of athletic subjects whose

arteries are relatively extensible and whose pulse wave velocity is low for their age, the observations fall below the mean line, while those from sedentary individuals whose arteries are relatively more rigid, and whose pulse wave velocity is higher than normal, fall above the line.

While, as has been previously indicated, the diastolic pressure shows little tendency to increase with age, the decrease in extensibility through loss of elasticity in the vessel walls necessitates an increase in the pulse pressure to enable the arteries to accept a ventricular output sufficient to meet the requirements of the tissues, and this accounts for the continued rise in systolic blood pressure with advancing years.

Having ascertained the normal relationship between age and arterial extensibility, and having defined the limits of variation which are met with in health, the task of investigating the modifications of arterial function occurring in disease should be simplified.

### SUMMARY AND CONCLUSIONS

- (1) A method is described whereby the velocity of the pulse wave in different segments of the arteries of the limbs may be measured with accuracy.
- (2) The arterial extensibility has been calculated from the velocity of transmission of the pulse wave in accordance with the formula:-

$$E = \left[ \frac{3.57}{V} \right]^2$$

where E = percentage increase in volume per  
mm. Hg. increase of pressure,

and V = velocity in metres per second.

While the use of a formula in the quantitative calculation of results is open to the criticism that the formula itself may be inaccurate, it will be conceded by all that, irrespective of any actual formula, extensibility bears an inverse relationship to pulse-wave velocity: thus, while the actual observations relate to measurements of the velocity of the pulse wave, for simplicity, the results are discussed in terms of extensibility.

- (3) On account of the variation in structure throughout the arterial tree, the values of pulse-wave velocity and extensibility obtained represent the mean values for the section of artery examined.
- (4) The mean extensibility of the brachial artery has been found in all cases to be greater than that of the radial artery.
- (5) Histological investigation indicates that the difference in extensibility between the brachial and radial artery is due to a difference in the structure of the two vessels, the brachial artery when examined microscopically exhibiting a more elastic structure than its more distal continuation.
- (6) While the results obtained from the brachial artery show a definite degree of uniformity, those obtained from the radial artery show considerable variation. The comparatively consistent results obtained by previous observers in estimating the mean pulse-wave velocity over the whole arm are due in large

measure to the uniformity in the velocity with which the pulse wave is transmitted in the brachial artery.

- (7) The effect of respiration has been studied, and while in different individuals there is considerable variation in the degree to which the extensibility of the arteries is altered by respiration, in all the subjects examined expiration was associated with a decrease in extensibility, due apparently to the rise in blood pressure which occurs during the expiratory phase.
- (8) The variation in arterial extensibility in response to changes of blood pressure has been investigated by altering the posture of the arm. By this means, differences in diastolic pressure amounting to 20 to 30 mm. Hg. can be produced. In all cases an increase in pressure was associated with a corresponding decrease in extensibility.

- (9) Both in the case of variations in blood pressure associated with respiration and in alterations produced by change of posture of the arm, the decrease in extensibility associated with a rise in pressure was more marked in the radial artery than in the brachial artery.
- (10) No general relationship between blood pressure and extensibility has been found, and it has been shown that, in fact, none can exist, in view of the variation in the structure of the arteries which is encountered, not only in individuals of different ages, but in subjects of the same age by reason of their physical development and the conditions under which their cardio-vascular systems have to function.
- (11) The relation between age and arterial extensibility has been investigated in one hundred and three healthy individuals of ages varying from 5 to 80 years. It has been shown that there is a progressive decrease in the



extensibility of the arteries with age. Between the ages of 10 and 70 the volume extensibility of the brachial artery, as estimated by the formula, is almost halved, while the volume extensibility of the radial artery is reduced to one-third.

- (12) The decrease in extensibility with age is more rapid in the early part of life. This is particularly noticeable in the case of the radial artery, in which vessel the greater part of the age decrease in extensibility occurs below the age of 30.
- (13) The histological investigation is in agreement with the experimental evidence, and from the foetal arteries examined, and those of the young child, it has been shown that in the early period of life, the radial artery, when compared with the brachial artery of the same subject, exhibits a degree of elasticity in structure which is not met with in adult subjects.

- (14) The relation between age and extensibility suggests that the increase in systolic pressure and in pulse pressure in accordance with age is a compensatory mechanism designed to enable the heart to maintain its output, in spite of the decrease in the extensibility of the arteries which accompanies advancing years.
- (15) Arterial extensibility has been investigated in the lower limb, and it has been shown that in the leg the more distal portion of the arterial branch exhibits the greater degree of extensibility.
- (16) Histological investigation does not disclose any marked difference in structure between the femoral and anterior tibial artery, and it would appear that the higher degree of extensibility found in the latter vessel is due to the lower blood pressure at which it functions, enabling a greater degree of extensibility to be exhibited.

- (17) The arteries in the lower limb show a lower degree of extensibility than those of the upper limb. This would appear to be due in part to a difference in structure, and in part to a variation in the blood pressure at which the vessels function.
- (18) Both in the arm and in the leg, the results obtained from the more extensible section of artery show a greater degree of uniformity. In addition to this, the results obtained from the arteries of the lower limb are less uniform than those obtained from the relatively more extensible vessels of the upper limb.
- (19) The relationship between uniformity of results and relative extensibility is due to the fact that in an inextensible artery the decrease in extensibility for a given rise of pressure is greater than that produced by an equal increase of pressure in an extensible vessel. The more inextensible vessels are thus affected to a greater degree by

slight changes in blood pressure induced by vaso-motor or other influences.

- (20) The variations observed in pulse-wave velocity show that the extensibility of the arteries is affected to a marked degree by various physiological factors. The greater the extensibility of the arteries, the greater is their change of volume for a given rise or fall of pressure. Hence, from the point of view both of the heart and of the capillary circulation, arterial extensibility is a factor of fundamental importance to the circulatory mechanism.

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